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Flow Field and Heat Transfer in a Model Gas Turbine Disk Cavity

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Abstract

We are carrying out experiments and computations in a model gas turbine disk cavity with the objective of understanding the turbulent flow field, ingestion of the mainstream gas into the cavity, and heat transfer. The experimental rig features a rotor-stator configuration which is simpler than in actual gas turbines but retains the important features of vanes on the stator disk, blades on the rotor disk, and realistic rim seals. Mainstream and secondary (cooling) air are provided at various flow rates to the rotor-stator system by separate blowers.

Thus far, the following results have been obtained:

- measured convective heat transfer coefficient and cooling effectiveness distributions on the rotor disk surface at various conditions with and without ingestion of mainstream air; the thermochromic liquid crystal technique has been used along with RTDs embedded in the rotor disk.

- measured circumferential static pressure distribution in the disk cavity (at the stator disk) and in the mainstream (at the outer shroud) at two axial locations between the stator vanes and rotor blades; a differential pressure transducer/scanivalve arrangement has been used.

- preliminary maps of instantaneous fluid velocity at several planar slices of the disk cavity; particle image velocimetry has been used.

- two-dimensional axisymmetric and three-dimensional calculations of the flowfield and heat transfer in the disk cavity (including the rotor disk surface) and the mainstream; the FLUENT/UNS code has been used.

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The usefulness of the preceding results to the development of advanced gas turbine systems for

power generation is as follows:

- they provide the turbine designers with quantitative information on heat transfer coefficient and cooling effectiveness distributions on the rotor disk surface in a cavity configuration which incorporates many of the important features of industrial gas turbines.

- they provide information on conditions which lead to the ingestion of mainstream gas into the disk cavity in presence of realistic rim seals.

- they provide information on the instantaneous velocity field in the disk cavity.

- they provide information on the two-dimensional axisymmetric and three-dimensional simulation capabilities of the commercial CFD code FLUENT/UNS.

At the present time, we are collaborating with:

- AlliedSignal Engines, Phoenix, Arizona - in both experiments and computations.

- Solar Turbines, San Diego, California - primarily, discussion of experiments and analyses conducted by us and by Solar Turbines at their facility.

- Institut für Thermische Strömungsmaschinen, Universität Karlsruhe, Germany - one graduate student from this institute has recently completed his Dipl. Ing. Thesis research in our laboratory.

During the third year of this project, we plan to:

- complete the flow pattern visualization experiments using particle image velocimetry.

- perform mainstream gas ingestion study via CO_2 (tracer gas) concentration measurement.

- continue three-dimensional flow and heat transfer computations using FLUENT/UNS.

Acknowledgments

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FLOW AND HEAT TRANSFER IN GAS TURBINE DISK CAVITIES SUBJECT TO NON-UNIFORM EXTERNAL PRESSURE FIELD

(DOE/SCERDC/AGTSR Sub-contract No. 95-01-SR033)

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Industry Participation:	AlliedSignal Engines (Jeff Howe, Yong W. Kim, Kuo-San Ho) Solar Turbines (M. Fox)

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OBJECTIVE

The objective is to understand the turbulent flow field and heat transfer in gas turbine disk cavities. The main issue is the potential for the hot gas ingestion from the main gas path into the disk cavities, particularly the first-stage disk cavity, and its effect on the rotor disk temperature.

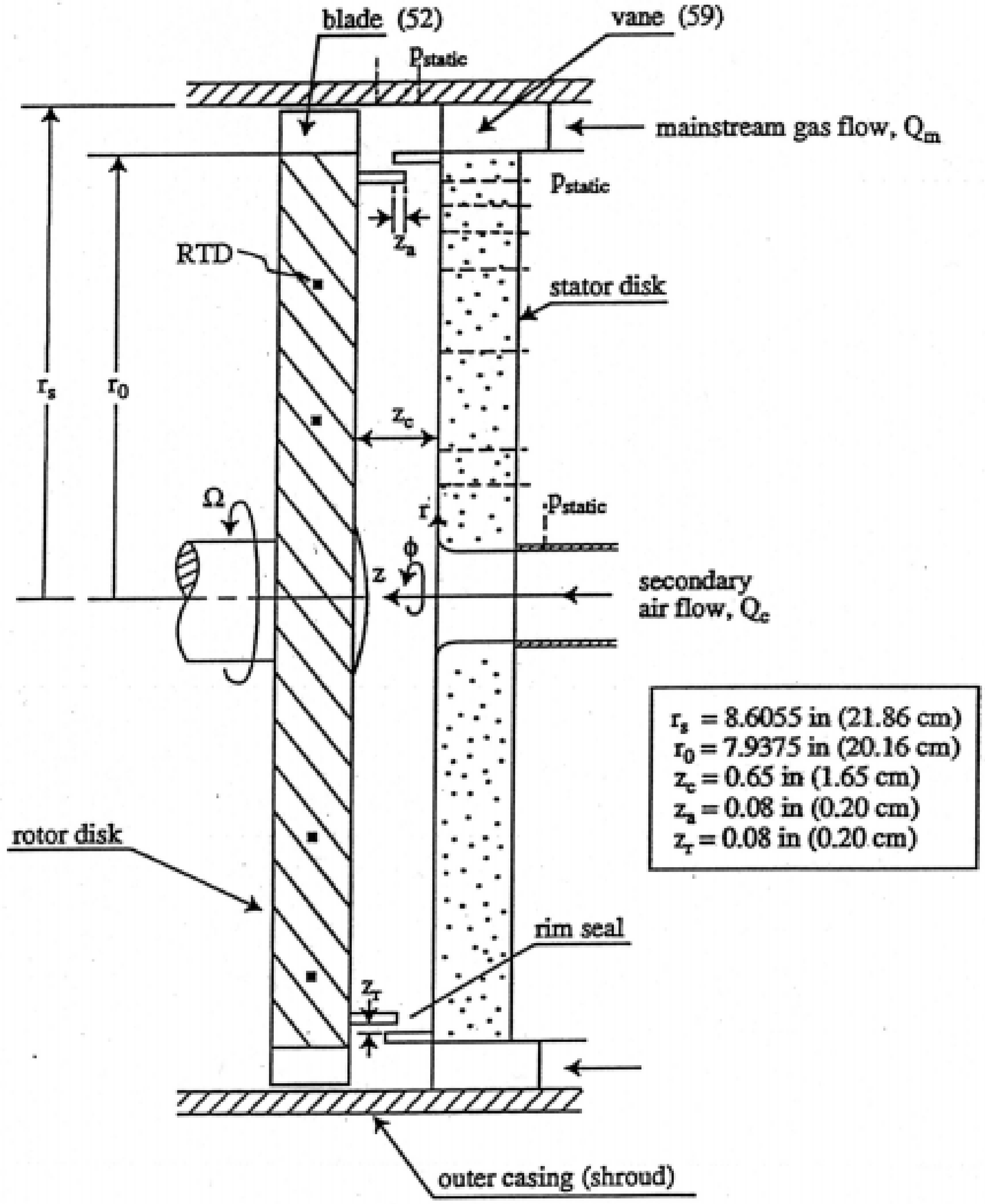
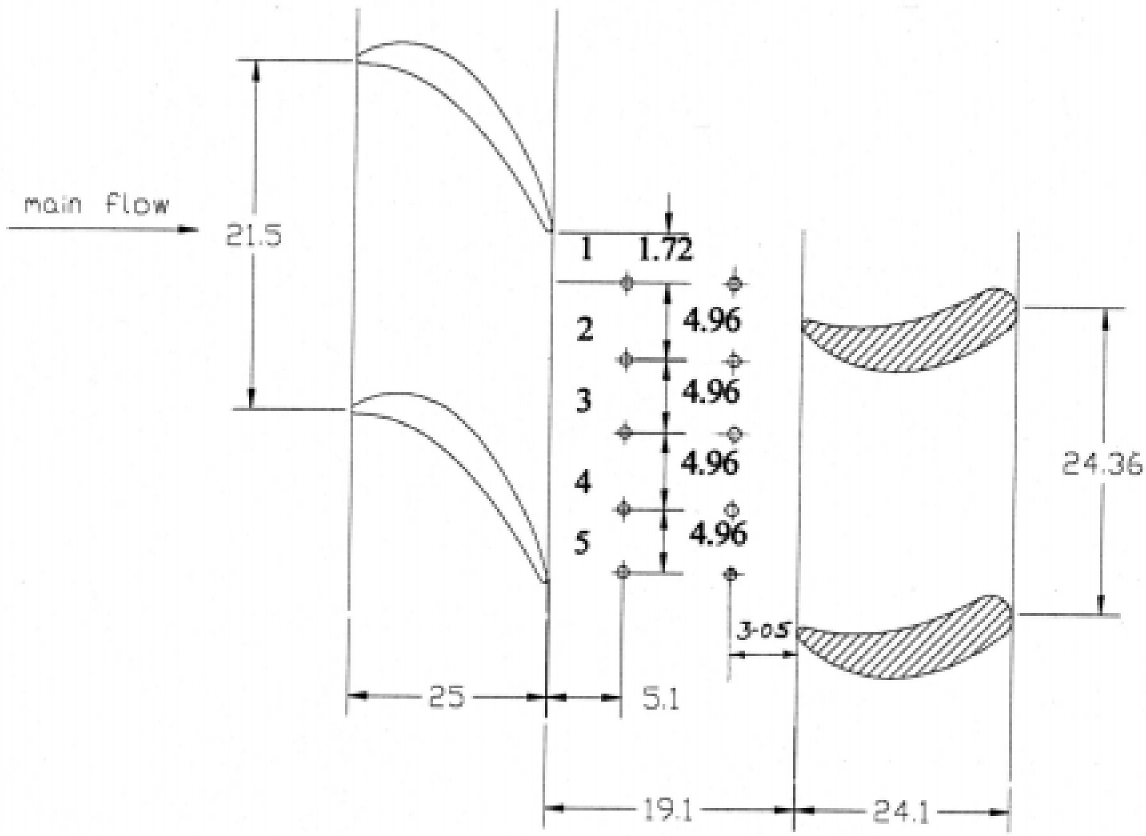


Fig. The disk cavity

LOCATION OF STATIC PRESSURE TAPS IN THE OUTER SHROUD REGION

(Downstream of the stator guide vanes)



(All dimensions are in mm)

1. Measurement of Local Convective Heat Transfer Coefficient and Cooling Effectiveness on Rotor Disk:
    - Method - Thermochromic Liquid Crystal
    - Status - Completed

2. Static Pressure Distribution Measurement in Main Gas Path (Circumferential) and Disk Cavity :
    - Method - Differential Pressure Transducer / Scanivalve
    - Status - Completed

3. CFD Simulation :
    - Method - Fluent/UNS
    - Status - 2 D Computations completed, 3 D Computations in progress

4. Measurement of Velocity Field in Disk Cavity :
    - Method - Particle Image Velocimetry
    - Status - Set up of PIV system completed, experiments in progress (to March, 1998)

5. Measurement of Gas Ingestion:
    - Method - Tracer Gas Concentration by NDIR Analysis
    - Status - Scheduled to Begin in March 1998

6. Additional Convective Heat Transfer and Cooling Effectiveness Measurements
    - Status - Scheduled in later part of 1998

RANGES OF EXPERIMENTAL PARAMETERS

Flow Parameters	Present Experiments
Rotational Reynolds number, Re_{Φ}	5.0×10^5 ---- 8.0×10^5
Main gas-path Reynolds number, Re_m	2.0×10^5 ---- 6.0×10^5
Main gas-path to rotor disk tip velocity ratio	to $\cong 1.0$
Secondary (cooling) air flow rate ratio, $Q_c/Q_{pumping}$	0.2 - 0.9
Exit flow angle at stator vane platform, β	55° - 60°
Geometric Parameters	
Cavity gap ratio, z_c/r_o	0.08
Rim seal axial overlap ratio, z_a/r_o	0.011
Radial seal clearance ratio, z_r/r_o	0.011

BASIC DEFINITIONS

Heat Transfer Coefficient

$$h(r) = \quad q_s''(r) / (T_s(r) - T_r(r))$$

Cooling Effectiveness :

$$\eta(r) = \quad (T_r(r) - T_m) / (T_c - T_m)$$

where :

q_s'' = heat flux

T_s = Rotor disk surface temperature

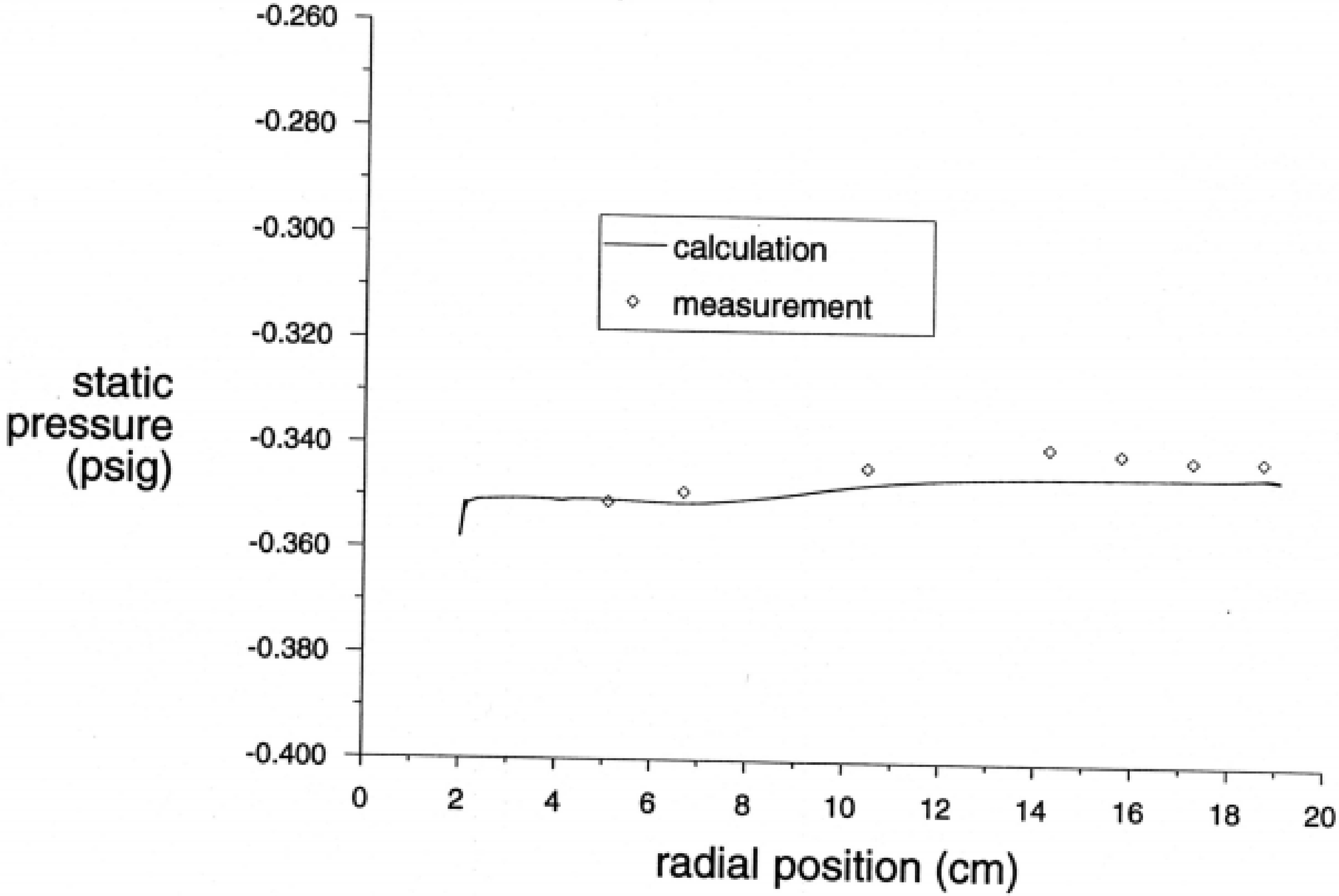
T_r = Reference temperature

T_m = Main flow air temperature

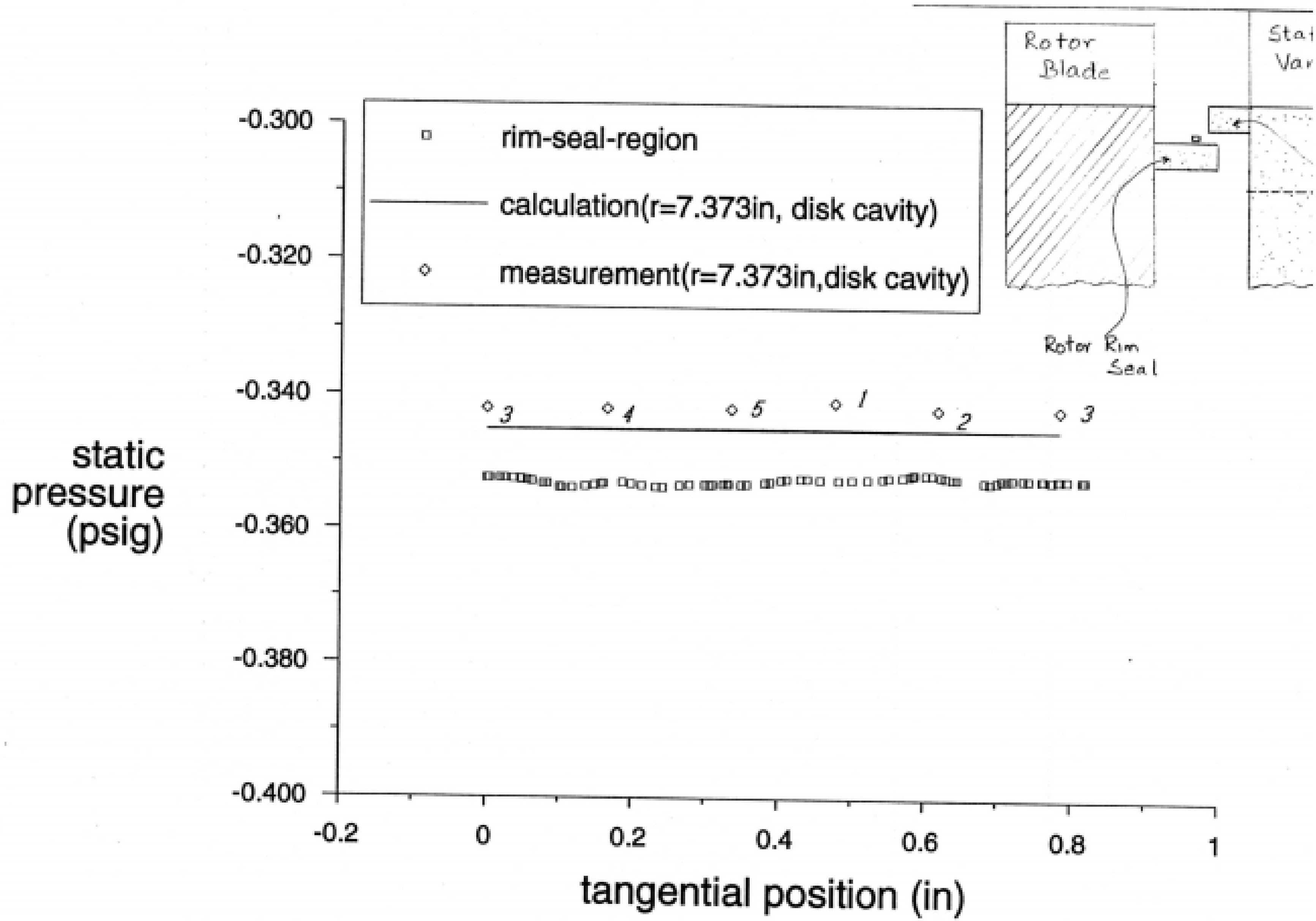
T_c = Secondary flow air temperature

EXPERIMENTAL CONDITION FOR EXPERIMENT 1

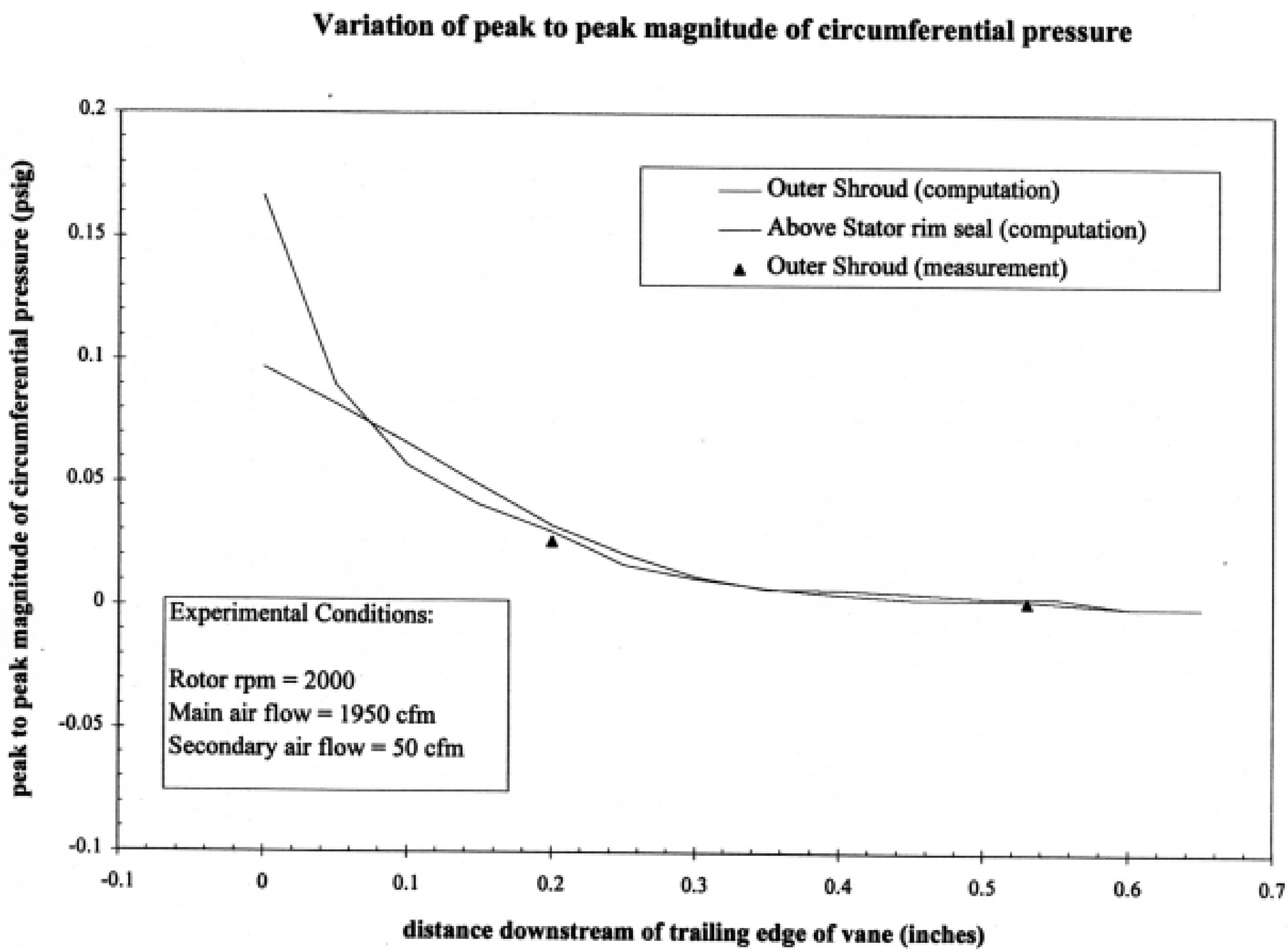
Mainstream air flow rate	:	$0.9204\ m^3/s$ (1950 cfm)
Rotor disk speed	:	2000 rpm
Rotational Reynolds Number ($Re_\Phi = \omega r_o^2/\nu$)	:	5.4×10^5
Turbulent Pumping flow rate ($Q_p = 0.0697\, \nu\, \pi\, r_o\, Re_\Phi^{0.8}$)	:	$0.02683\ m^3/s$
Main Gas path Reynolds Number: $Re_m = (\rho V_m r_o/\mu)$		5.2×10^5
Main Gas path to Disk tip velocity ratio ($V_m/\omega r_o$)	:	0.97
Secondary air flow rate (Q_c)	:	$0.0236\ m^3/s$ (50 cfm)
Q_c/Q_p	:	0.88
C_w ($\rho Q_c / \mu r_o$)	:	7364
Turbulence Parameter ($\lambda_t = Cw/Re_\Phi^{0.8} = 0.219\, m_c/m_p$)	:	0.192



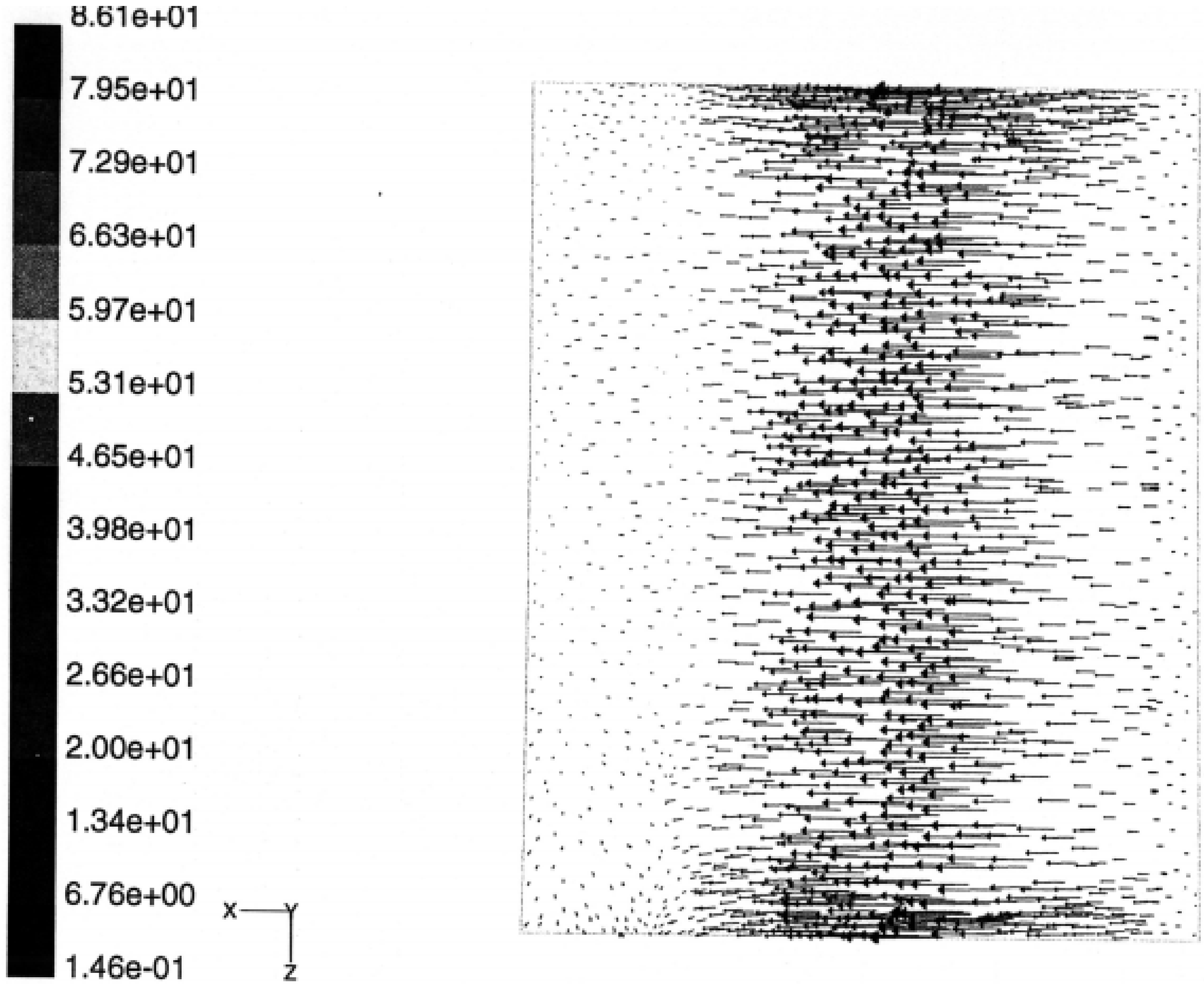
static pressure at the stator surface (3D,50cfm,2000rpm)



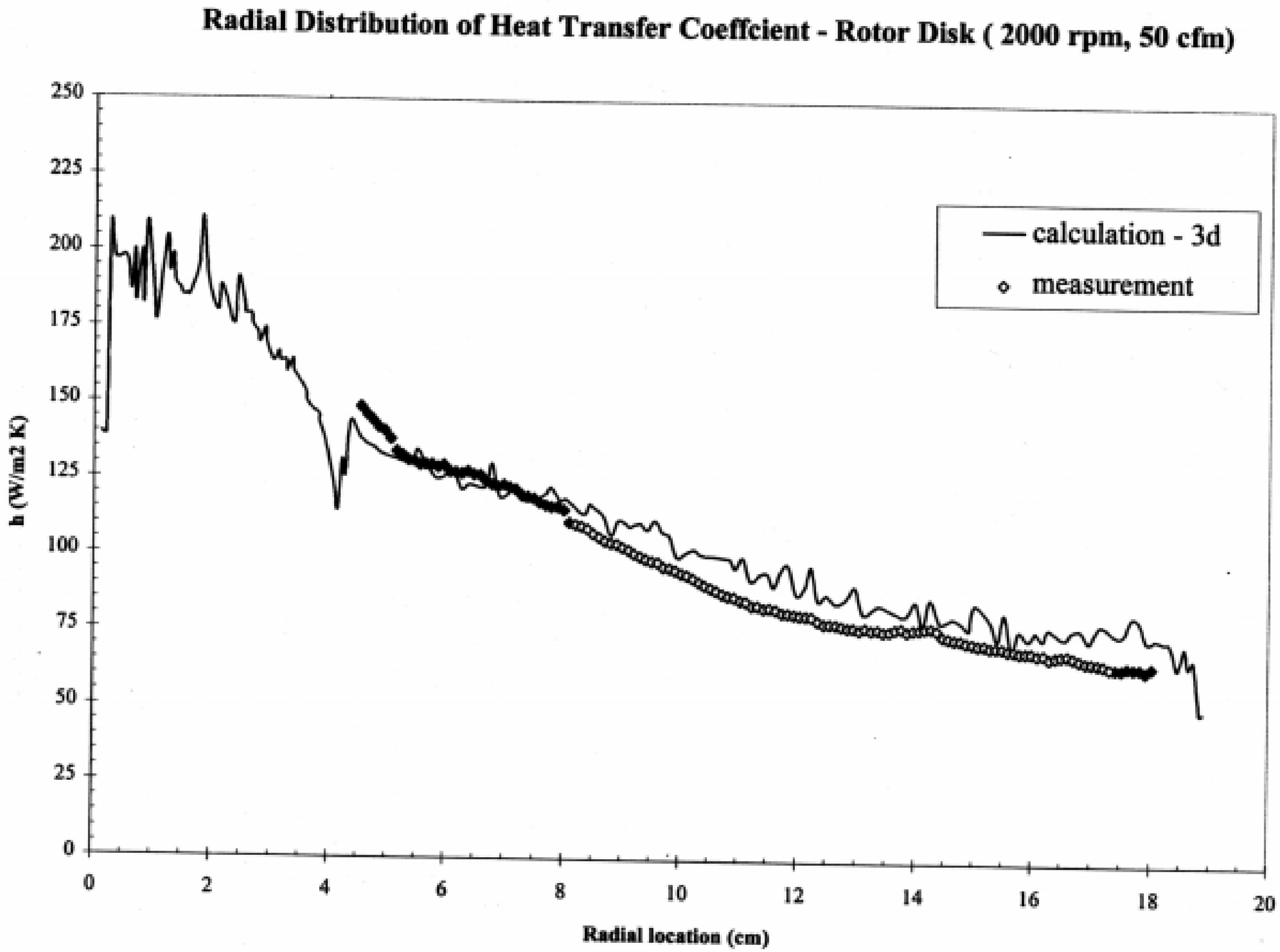
static pressure at the rim seal and disk cavity (3D,50cfm,2000rpm)



Variation of peak to peak magnitude of circumferential pressure
Outer Shroud (computation)
Above Stator rim seal (computation)
Outer Shroud (measurement)
Experimental Conditions:
Rotor rpm = 2000
Main air flow = 1950 cfm
Secondary air flow = 50 cfm
peak to peak magnitude of circumferential pressure (psig)
distance downstream of trailing edge of vane (inches)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

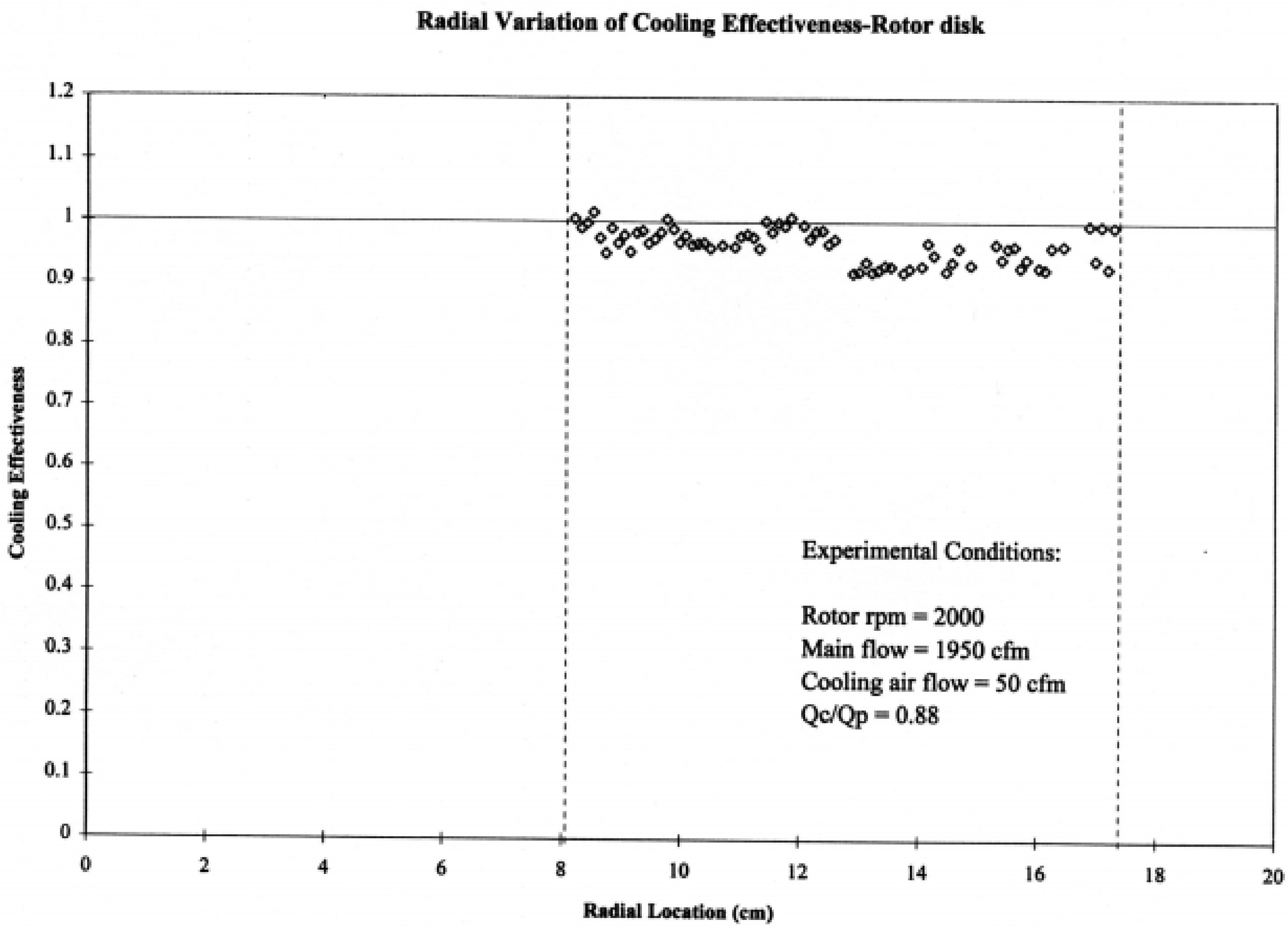


velocity vectors at the rim seal region (3D,50cfm,2000rpm)

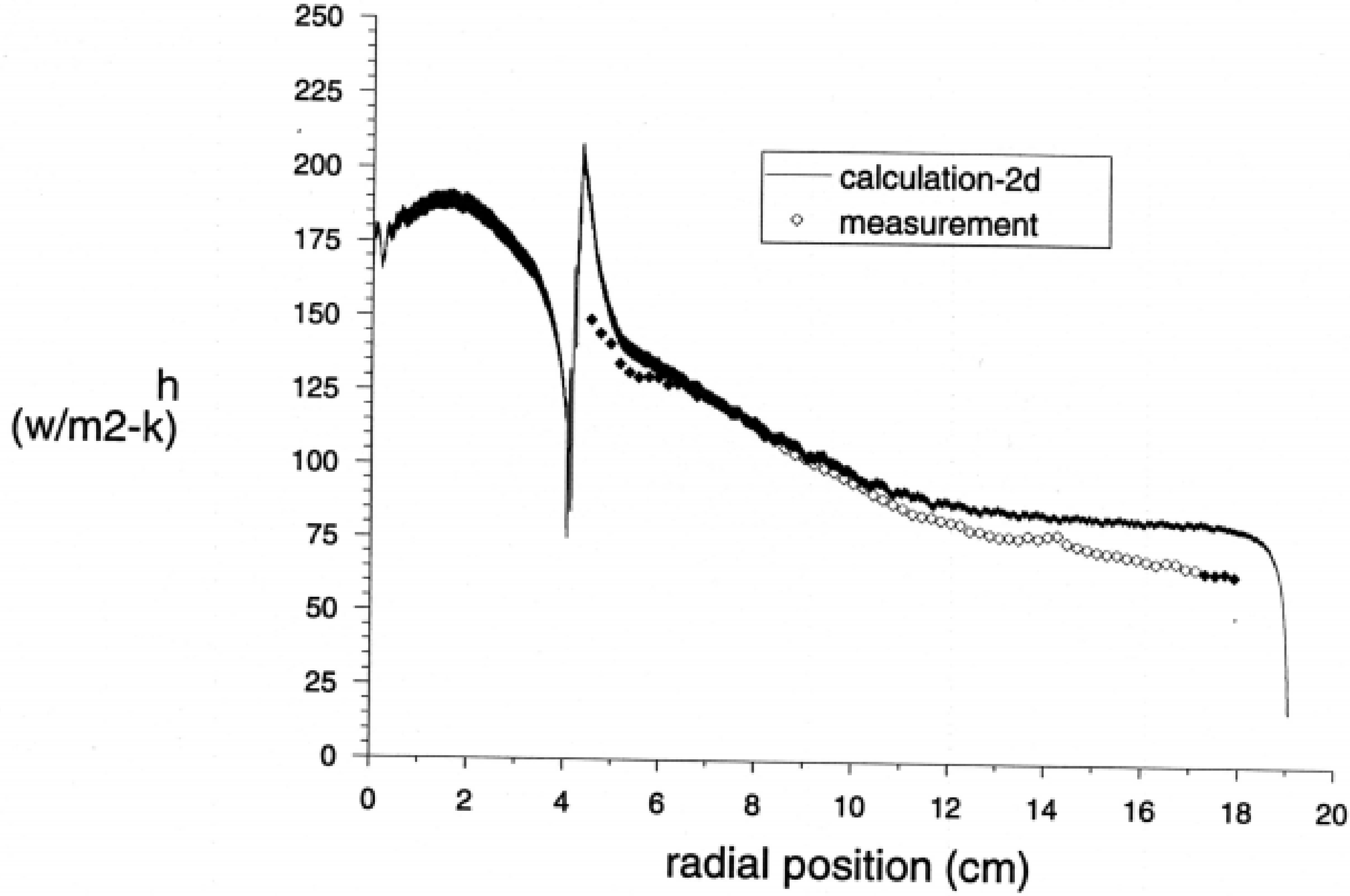


Radial Distribution of Heat Transfer Coeffcient - Rotor Disk (2000 rpm, 50 cfm)
calculation - 3d
measurement
h (W/m2 K)
Radial location (cm)

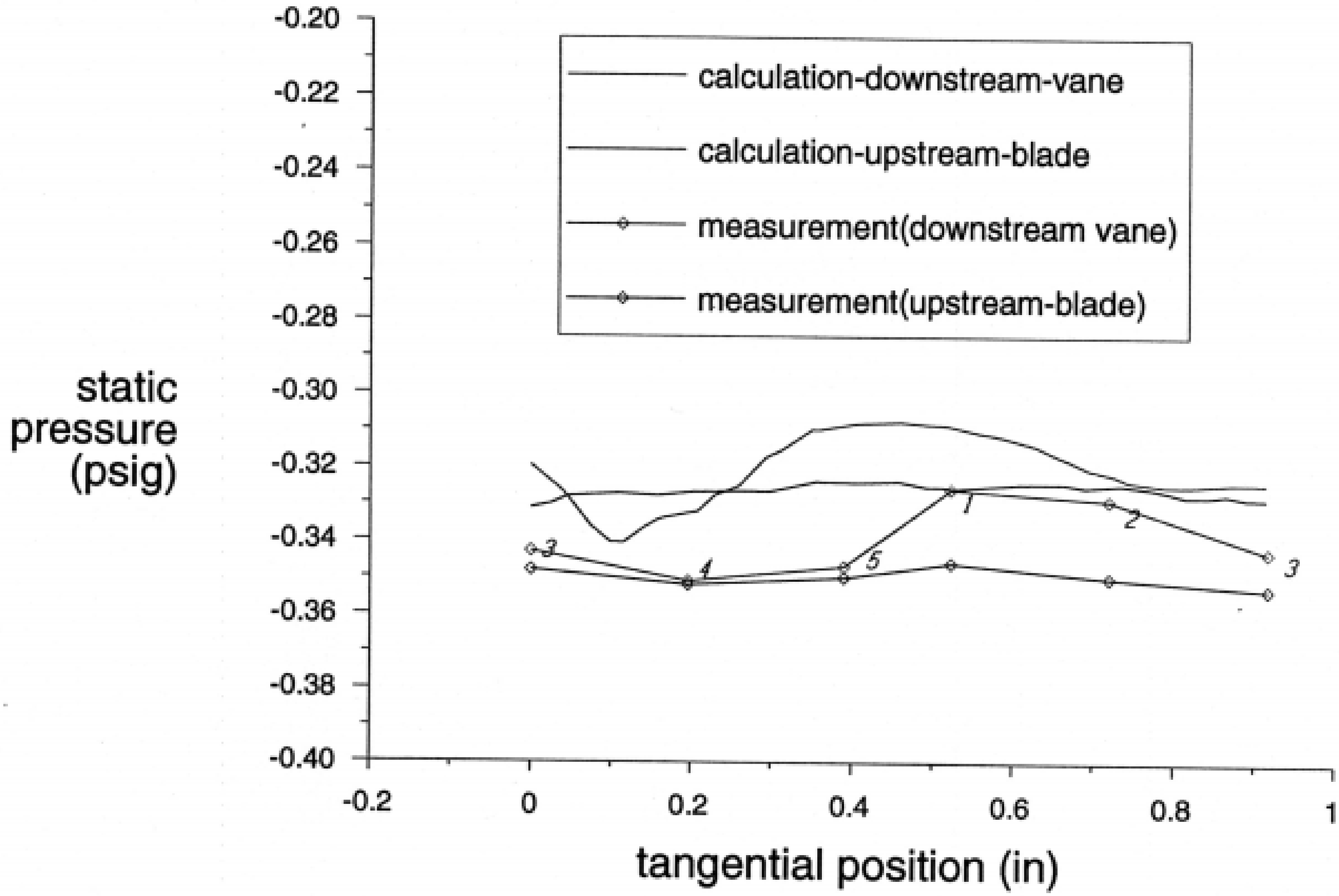
Fig 4.4



Radial Variation of Cooling Effectiveness-Rotor disk
Cooling Effectiveness
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2
4
6
8
10
12
14
16
18
20
Radial Location (cm)
Experimental Conditions:
Rotor rpm = 2000
Main flow = 1950 cfm
Cooling air flow = 50 cfm
Qc/Qp = 0.88



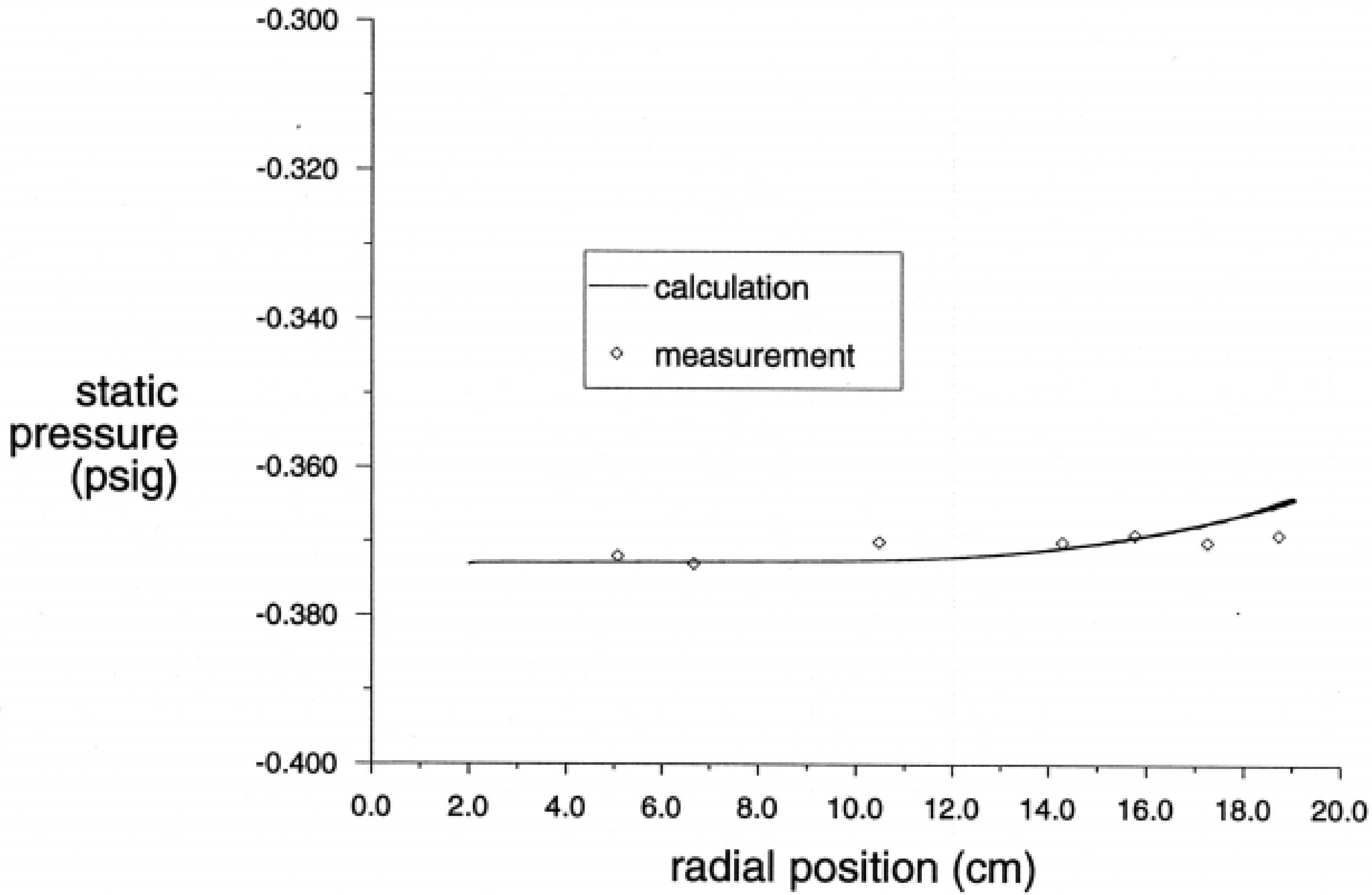
Radial Distribution of Heat Transfer Coefficient at 2000rpm,50cfm



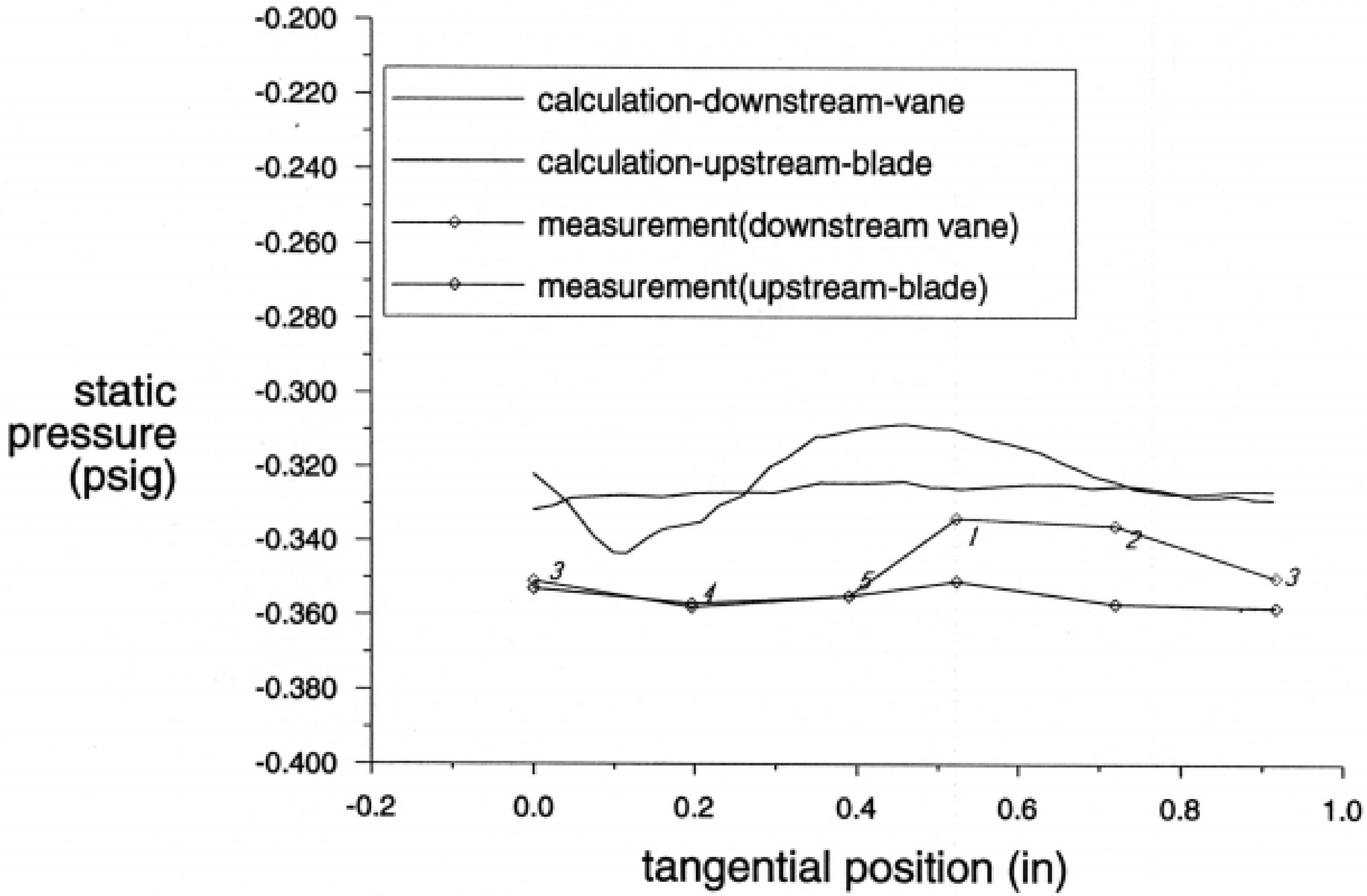
static pressure at the outer shroud (3D,50cfm,2000rpm)

EXPERIMENTAL CONDITION FOR EXPERIMENT 2

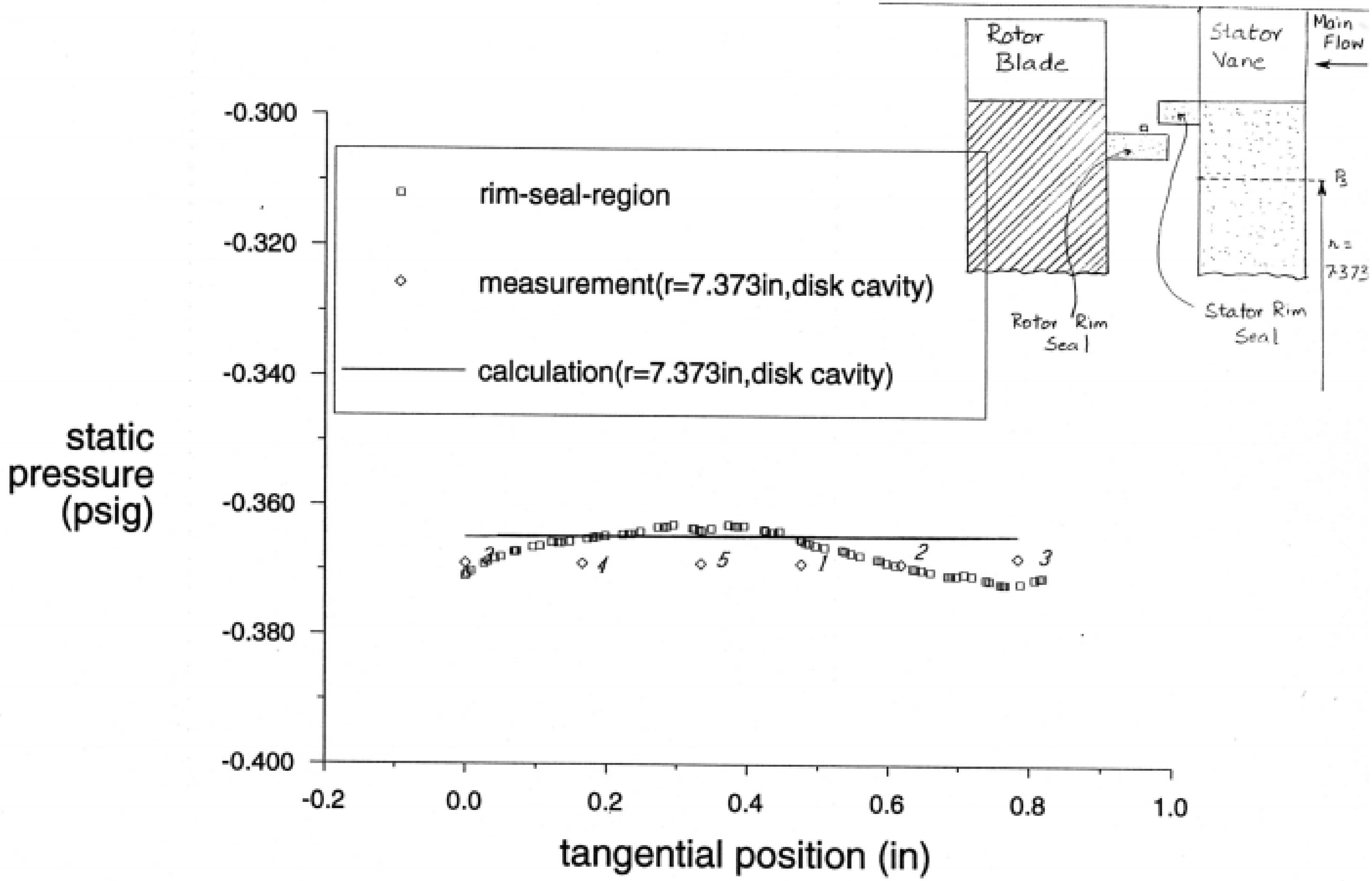
Mainstream air flow rate	:	$0.9204\ m^3/s$ (1950 cfm)
Rotor disk speed	:	2000 rpm
Rotational Reynolds Number ($Re_\Phi = \omega . r_o^2/\nu$)	:	5.4×10^5
Turbulent Pumping flow rate ($Q_p = 0.0697\ \nu\ \pi\ r_o\ Re_\Phi^{0.8}$)	:	$0.02683\ m^3/s$
Main Gas path Reynolds Number: $Re_m = (\rho V_m\ r_o/\mu)$		5.2×10^5
Main Gas path to Disk tip velocity ratio ($V_m/\omega\ r_o$)	:	0.97
Secondary air flow rate (Q_c)	:	$0.0047\ m^3/s$ (10 cfm)
$Q_c/\ Q_p$	:	0.18
$C_w\ (\rho Q_c\ /\ \mu\ r_o)$	:	1473
Turbulence Parameter ($\lambda_t = Cw/\ Re_\Phi^{0.8} = 0.219\ m_c/m_p$)	:	0.038



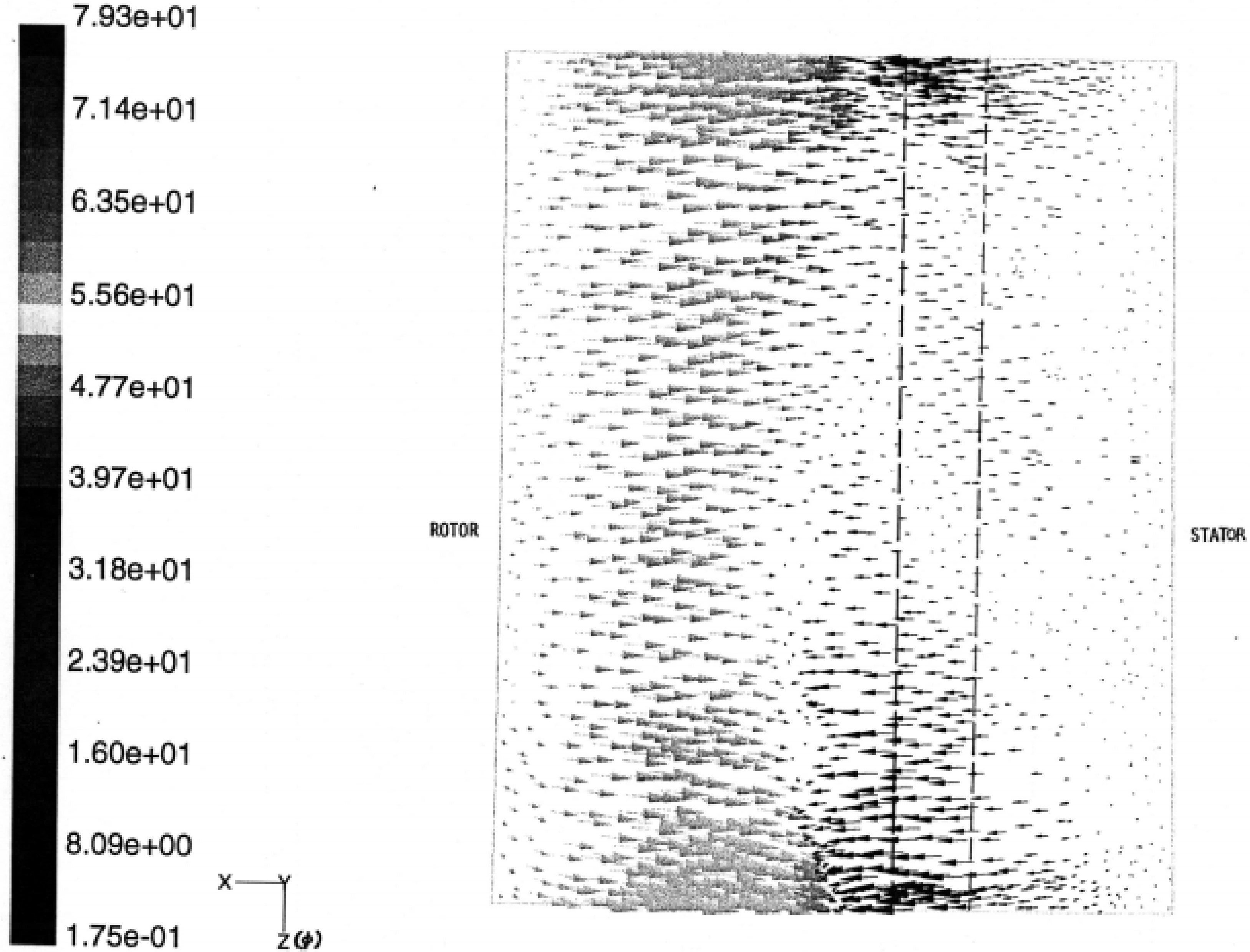
static pressure at the stator surface (3D,10cfm,2000rpm)



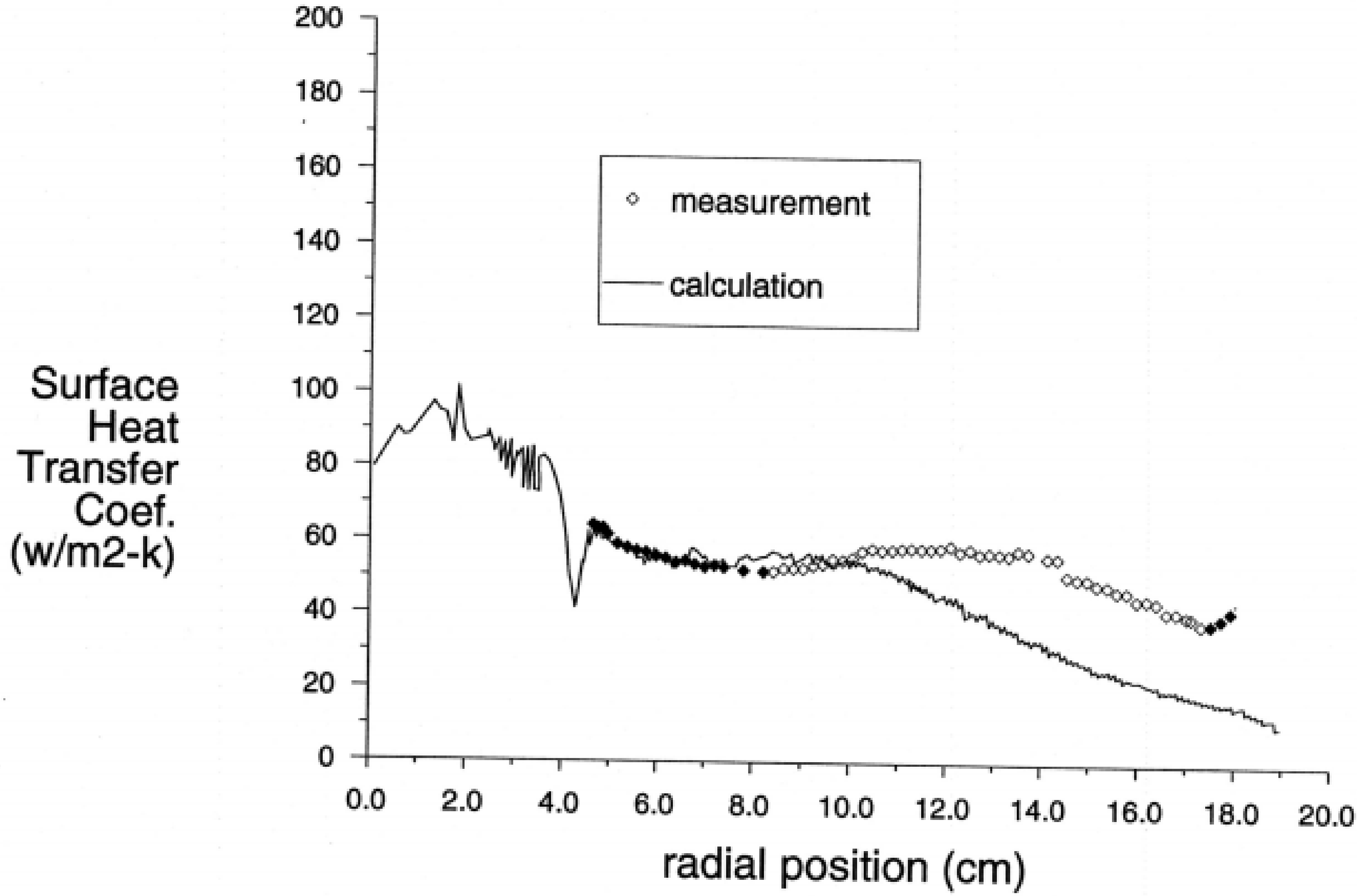
static pressure at the outer shroud (3D,10cfm,2000rpm)



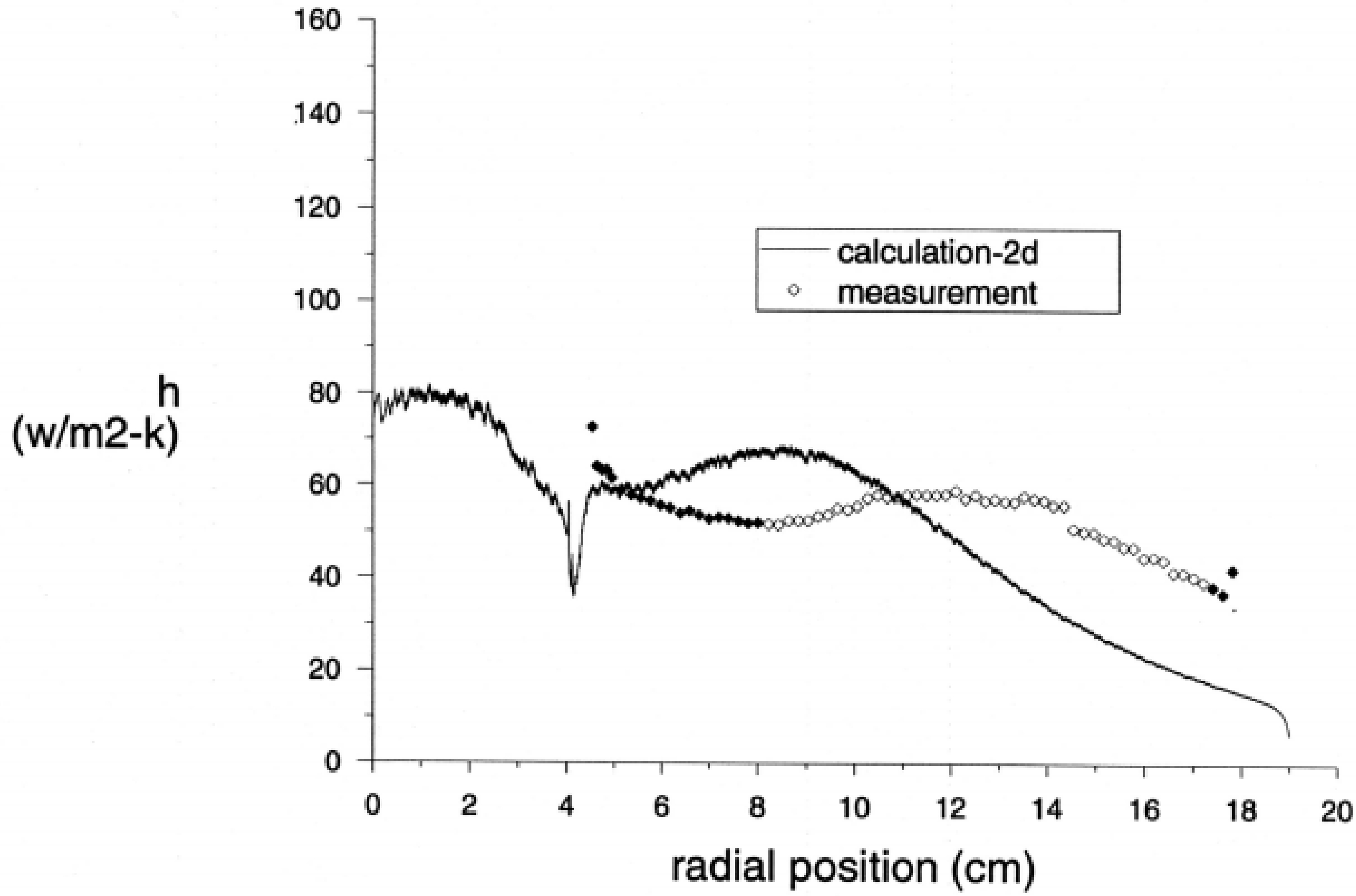
: pressure at the rim seal and disk cavity (3D,10cfm,2000rpm)



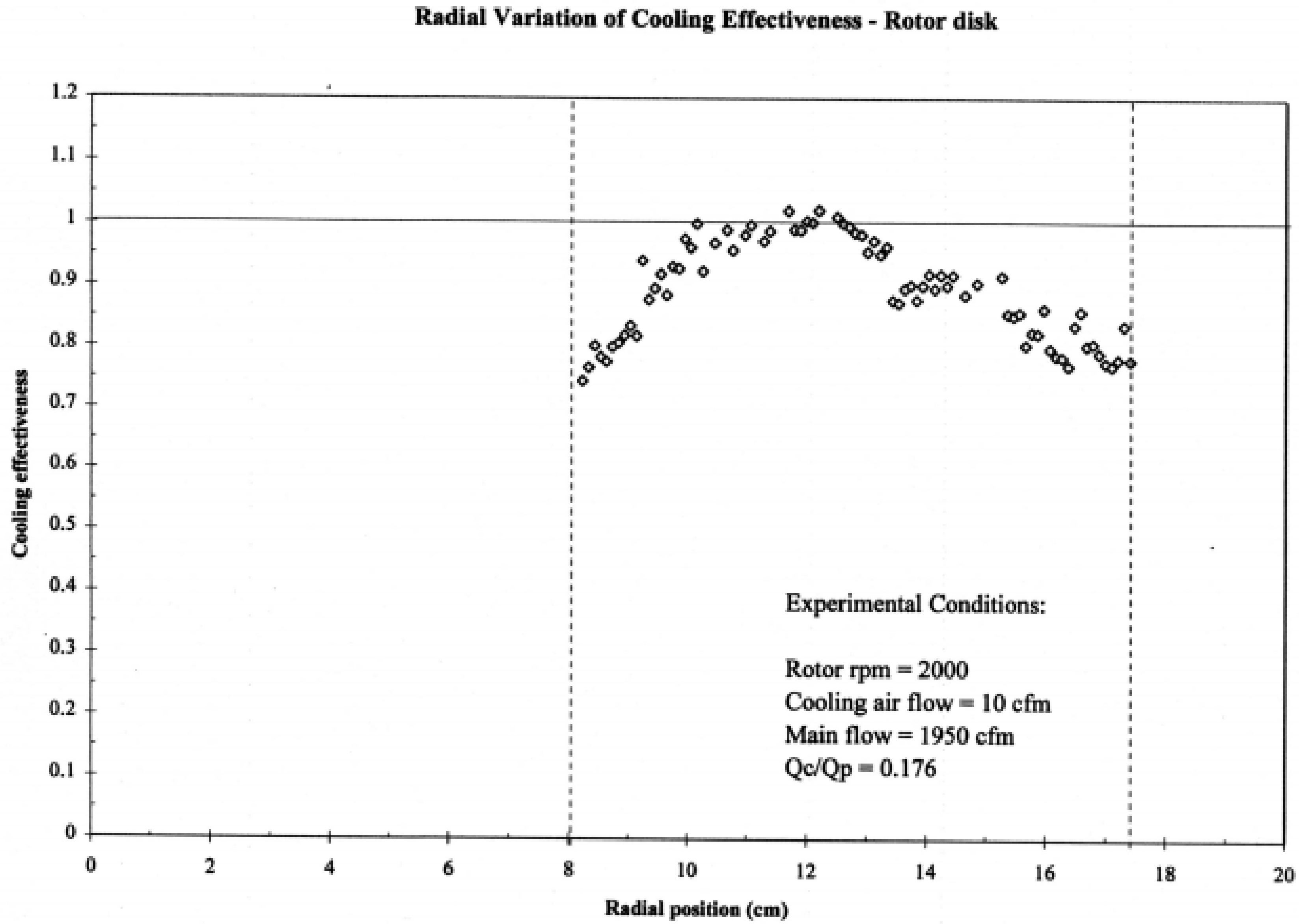
velocity vectors at the rim seal region (3D,10cfm,2000rpm)



surface heat transfer coefficient at the rotor surface (3D,10cfm,2000rpm)



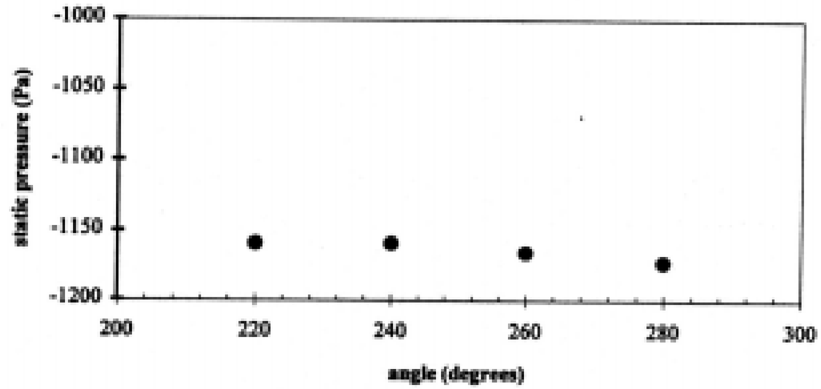
Radial Distribution of Heat Transfer Coefficient at 2000rpm,10cfm


Radial Variation of Cooling Effectiveness - Rotor disk
Cooling effectiveness
Radial position (cm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
0
2
4
6
8
10
12
14
16
18
20
Experimental Conditions:
Rotor rpm = 2000
Cooling air flow = 10 cfm
Main flow = 1950 cfm
Qc/Qp = 0.176

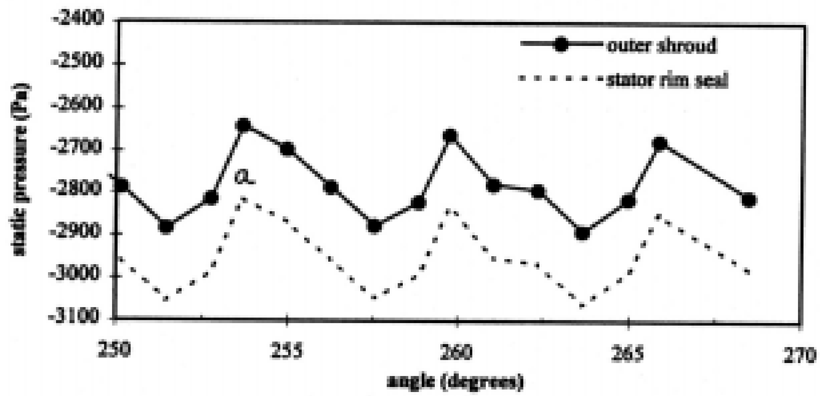
EXPERIMENTAL CONDITION FOR EXPERIMENT 3

Mainstream air flow rate	:	$0.8967\ m^3/s$ (1900 cfm)
Rotor disk speed	:	3000 rpm
Rotational Reynolds Number ($Re_\Phi = \omega.\ r_o^2/\nu$)	:	8.0×10^5
Turbulent Pumping flow rate ($Q_p = 0.0697\ \nu\ \pi\ r_o\ Re_\Phi^{0.8}$)	:	$0.03713\ m^3/s$
Main Gas path Reynolds Number: $Re_m = (\ \rho V_m\ r_o/\mu)$		5.1×10^5
Main Gas path to Disk tip velocity ratio ($V_m/\omega\ r_o$)	:	0.63
Secondary air flow rate (Q_c)	:	$0.0142\ m^3/s$ (30 cfm)
$Q_c/\ Q_p$	:	0.38
$C_w\ (\rho Q_c\ /\ \mu\ r_o)$	:	4419
Turbulence Parameter ($\lambda_t = Cw/\ Re_\Phi^{0.8} = 0.219\ m_c/m_p$)	:	0.083

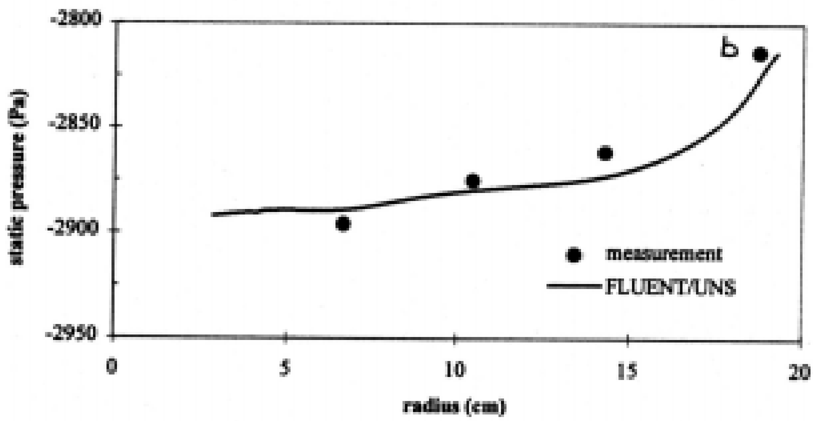
3000 rotor rpm, 30 cfm cooling air flow



Static pressure in the outer shroud, upstream of stator vanes



Static pressure in the outer shroud, downstream of stator vanes

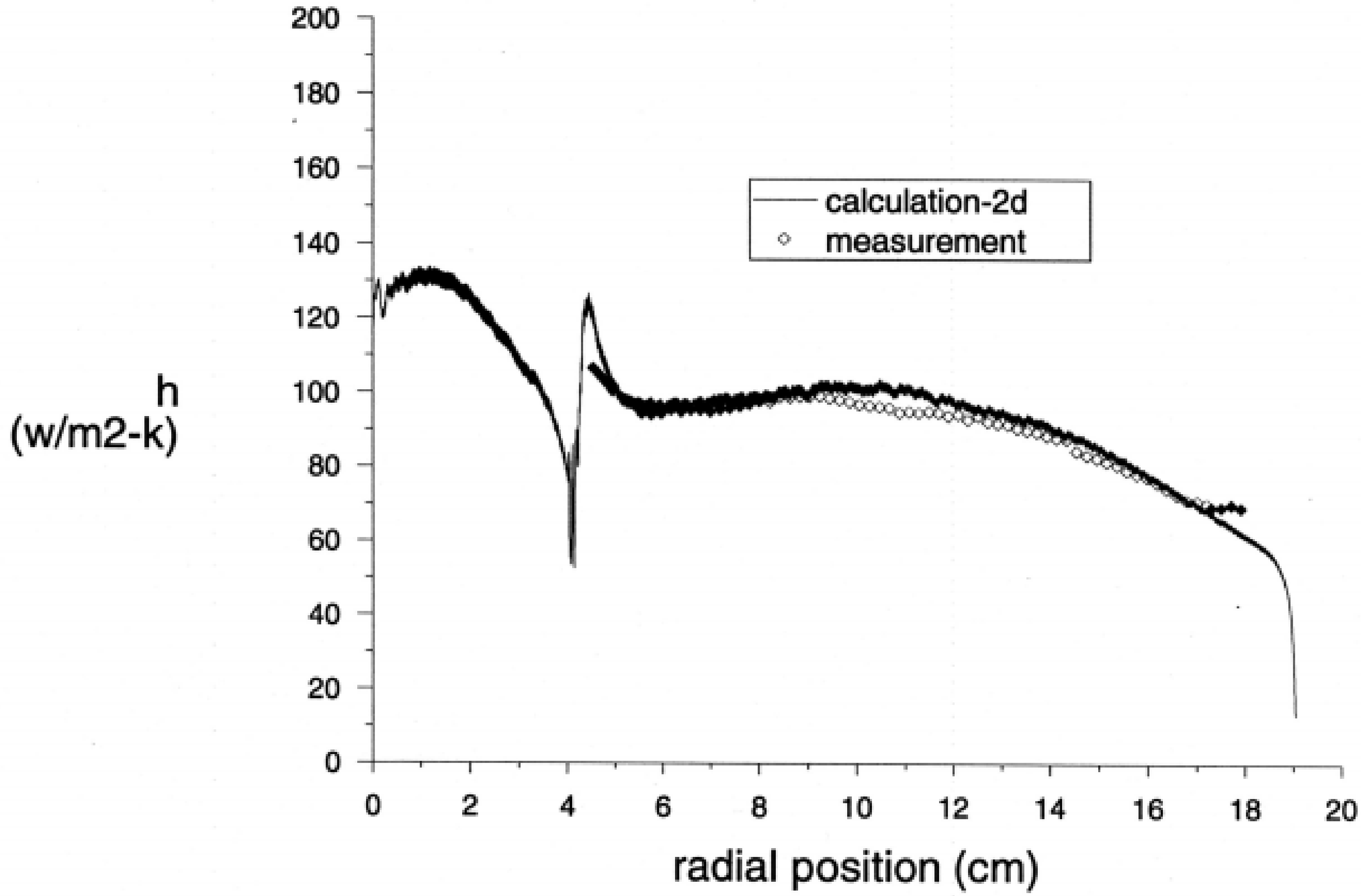


Static pressure distribution in the disk cavity

Pa = -2814 Pa

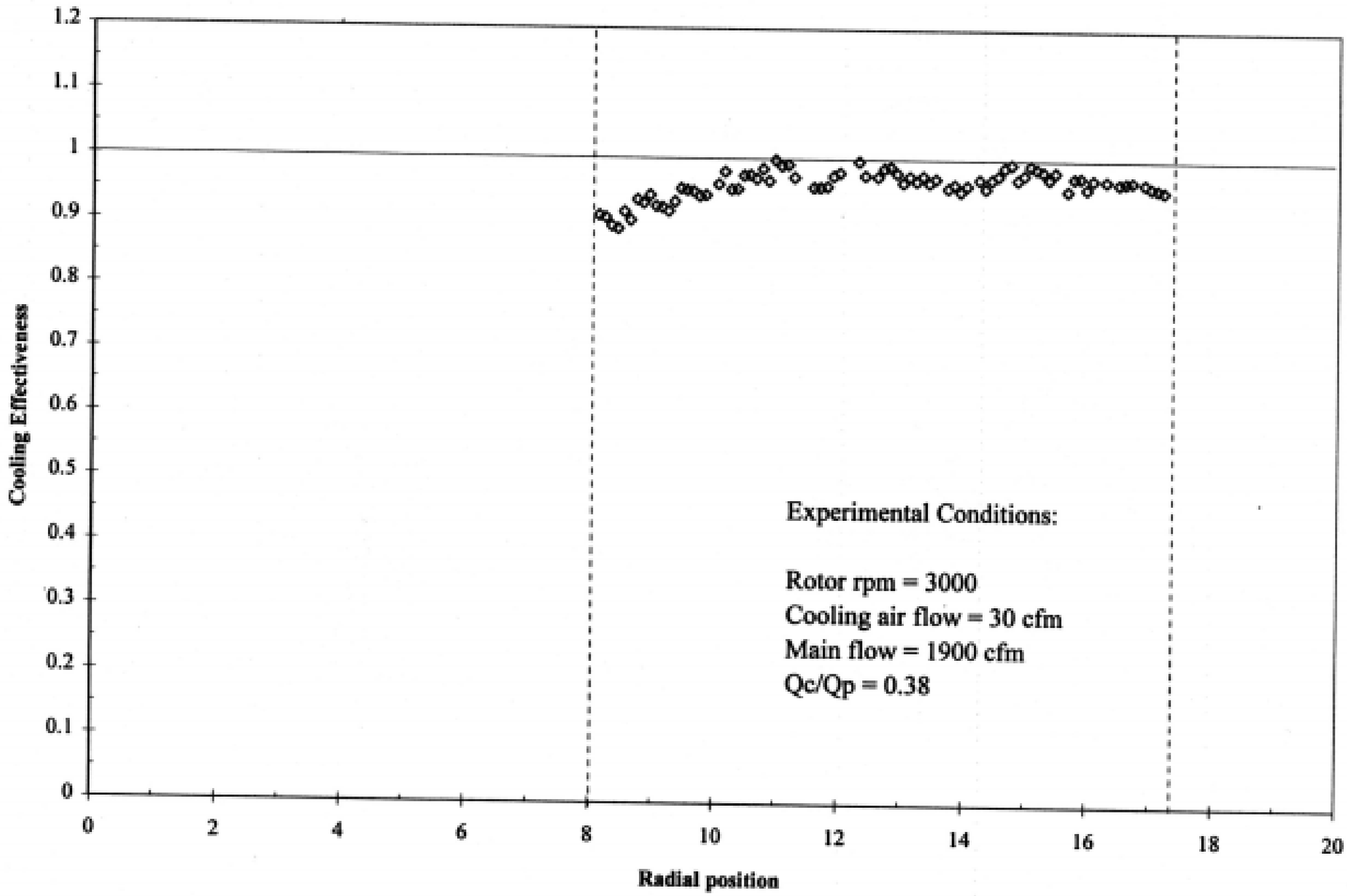
Pb = -2813 Pa

Pa-Pb= -1 Pa



Radial Distribution of Heat Transfer Coefficient (3000rpm,30cfm)

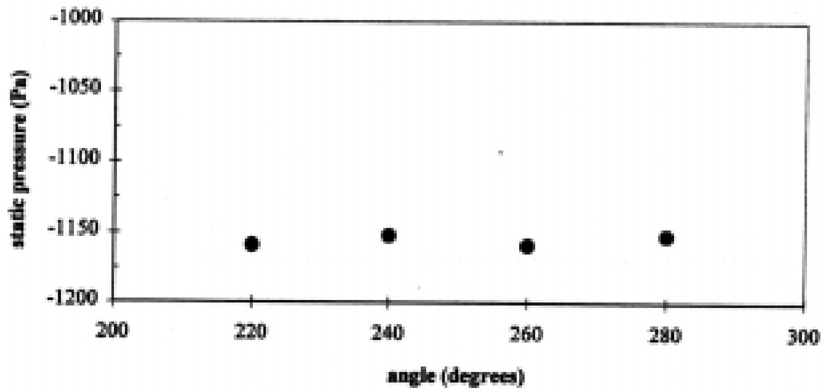
Radial Variation of Cooling Effectiveness - Rotor disk



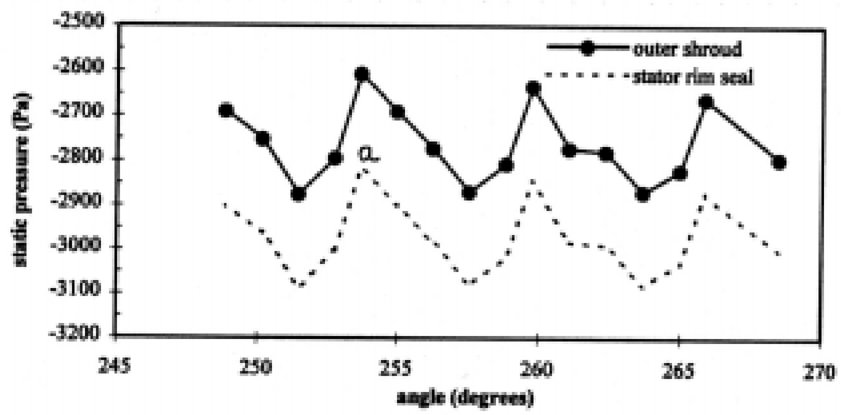
EXPERIMENTAL CONDITION FOR EXPERIMENT 4

Mainstream air flow rate	:	0.8967 m^3/s (1900 cfm)
Rotor disk speed	:	3000 rpm
Rotational Reynolds Number ($Re_\Phi = \omega . r_o^2/\nu$)	:	8.0×10^5
Turbulent Pumping flow rate ($Q_p = 0.0697\ \nu\ \pi\ r_o\ Re_\Phi^{0.8}$)	:	0.03713 m^3/s
Main Gas path Reynolds Number: $Re_m = (\rho V_m r_o/\mu)$		5.1×10^5
Main Gas path to Disk tip velocity ratio ($V_m/\omega\ r_o$)	:	0.63
Secondary air flow rate (Q_c)	:	0.0094 m^3/s (20 cfm)
Q_c/ Q_p	:	0.26
$C_w\ (\rho Q_c / \mu\ r_o)$	:	2946
Turbulence Parameter ($\lambda_t = Cw/ Re_\Phi^{0.8} = 0.219\ m_c/m_p$)	:	0.056

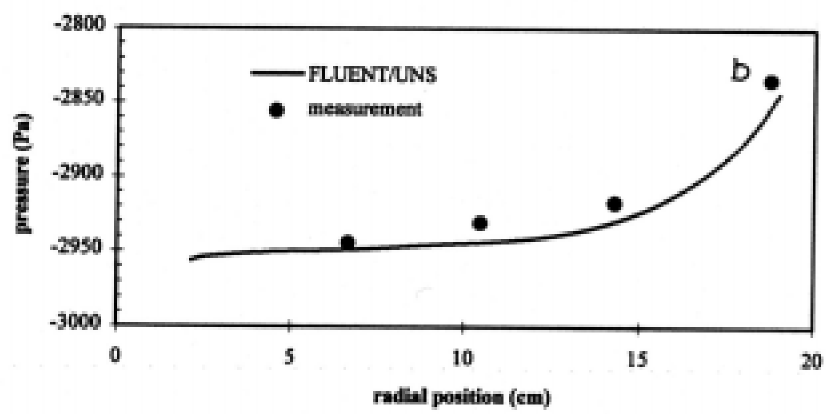
3000 rotor rpm, 20 cfm cooling air flow



Static pressure in the outer shroud, upstream of stator vanes



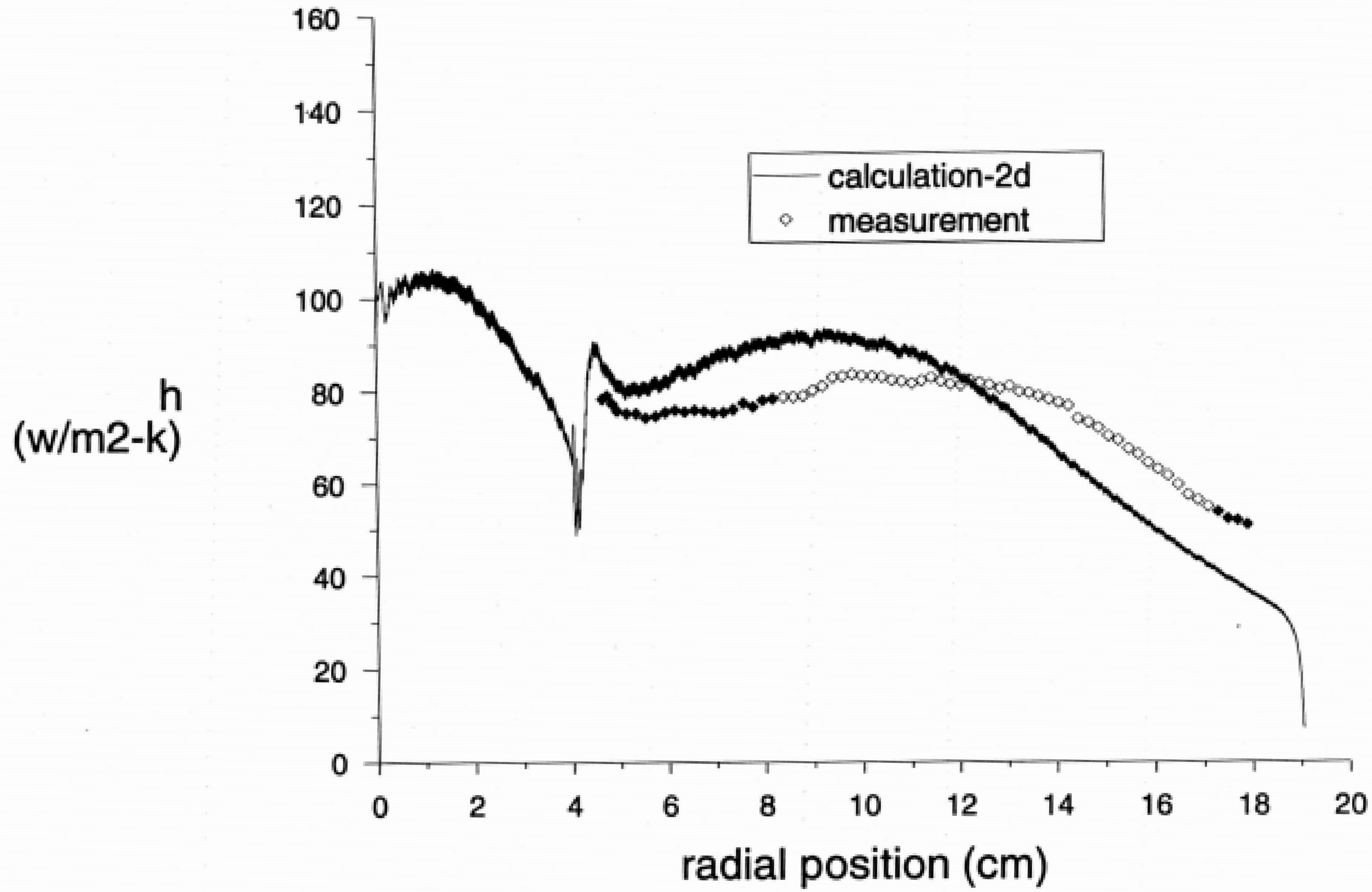
Static pressure in the outer shroud, downstream of vanes



Static pressure distribution in the disk cavity

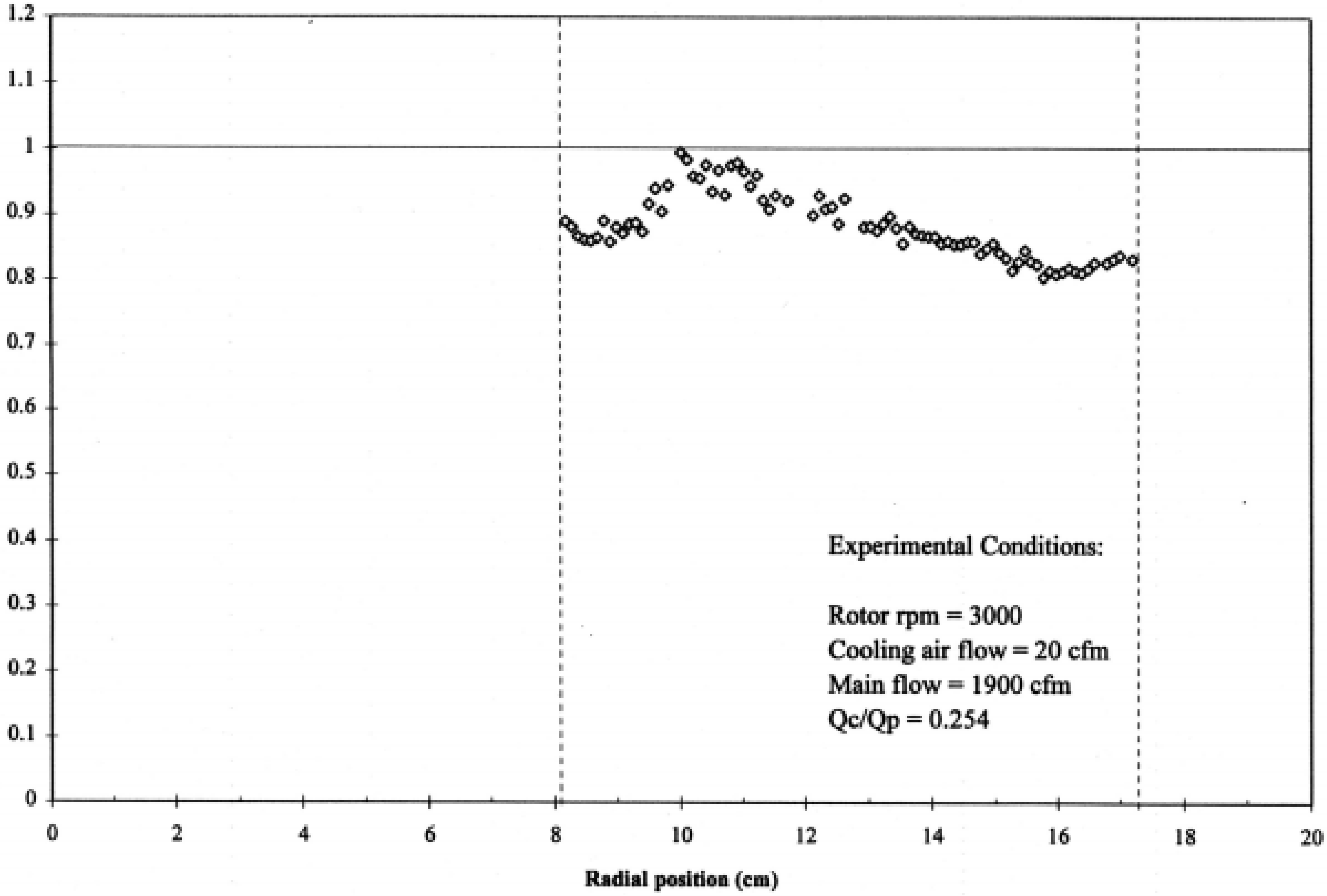
Pa= -2817 Pa
Pb= - 2834 Pa

Pa - Pb= + 17 Pa



Radial Distribution of Heat Transfer Coefficient at 3000rpm,20cfm

Radial Variation of Cooling Effectiveness - Rotor disk



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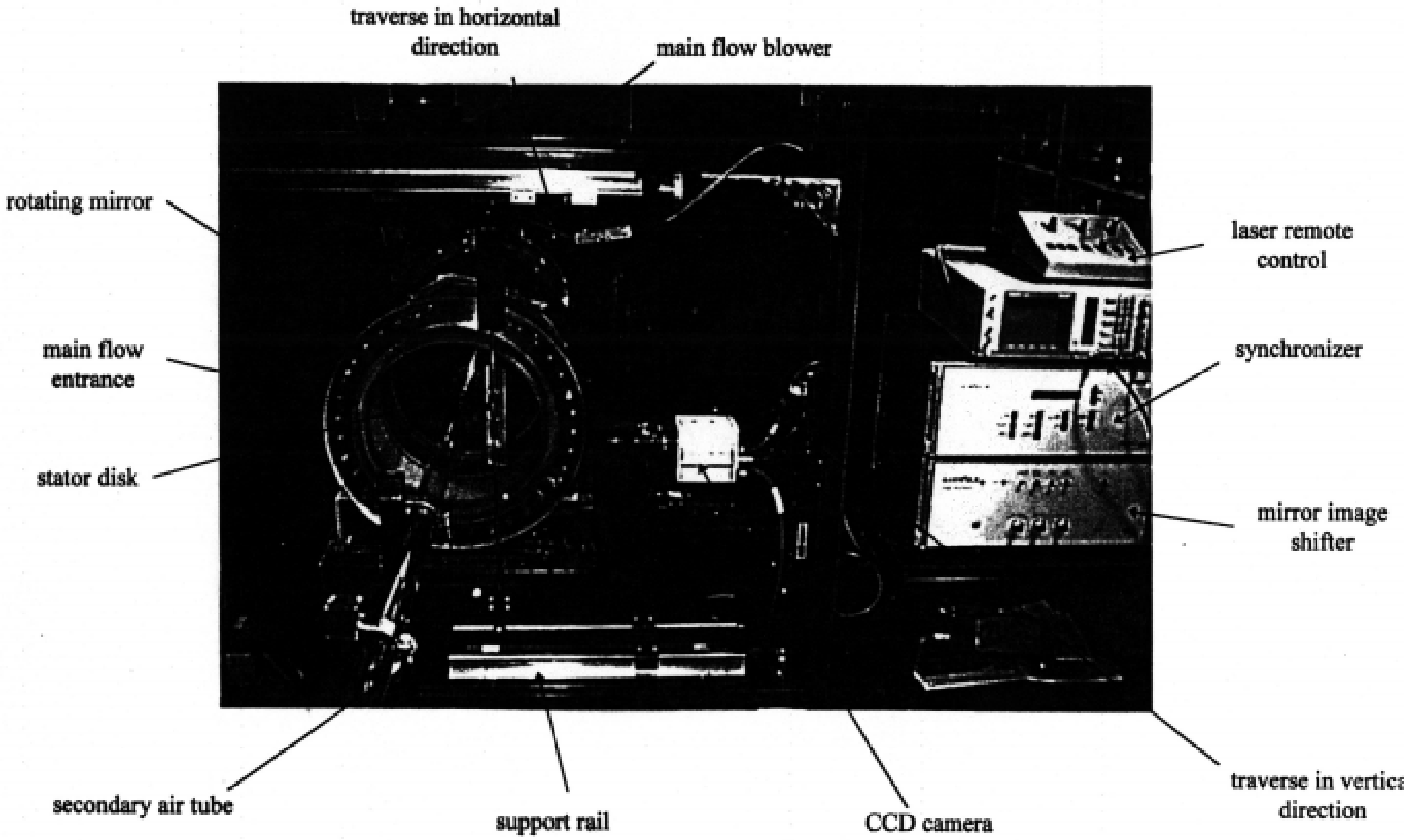
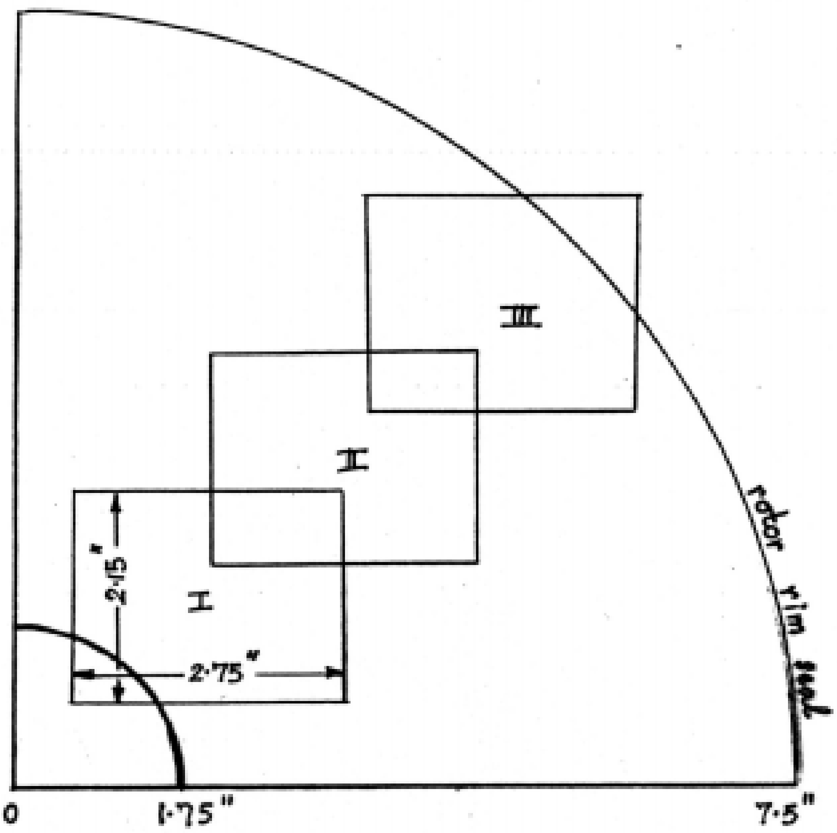

traverse in horizontal direction
main flow blower
rotating mirror
main flow entrance
stator disk
secondary air tube
support rail
CCD camera
laser remote control
synchronizer
mirror image shifter
traverse in vertica
direction

PIV

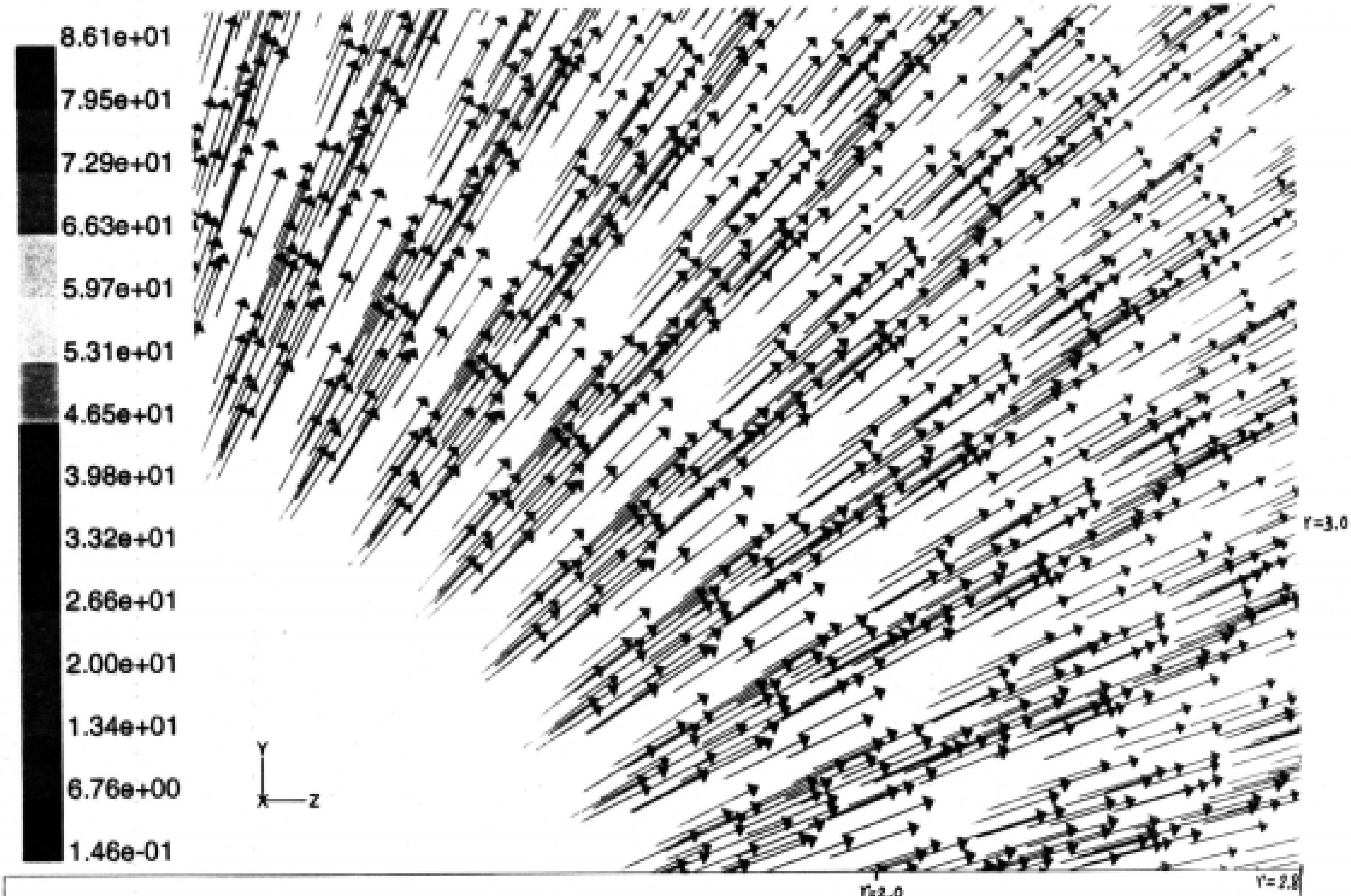


Location of the interrogation regions in the disk cavity
(PIV)

2mm from the rotor surface
x = 2" y = 2"
Main flow = 1950 cfm
Cooling flow = 50 cfm
rotor rpm =2000

I

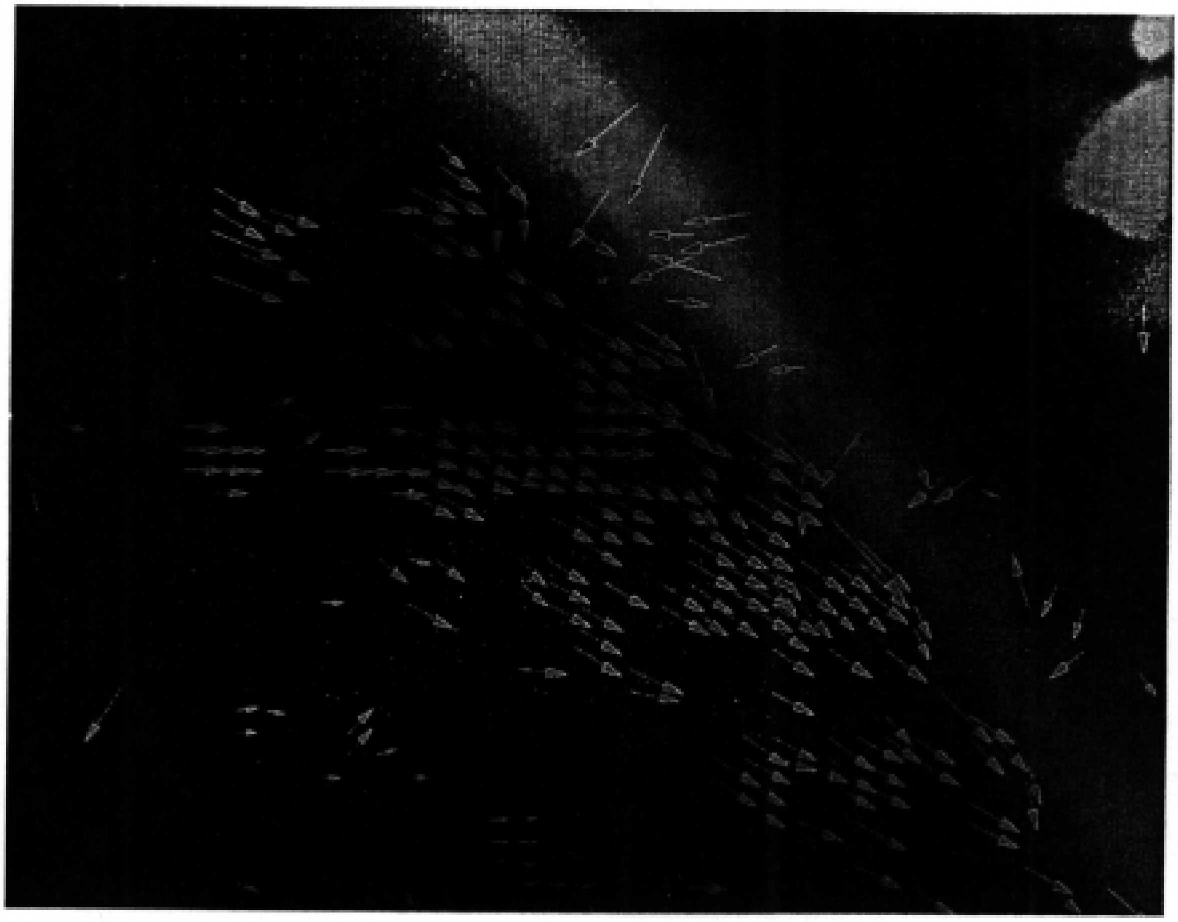
13 m/s



velocity vectors (50cfm,2000rpm,d=2mm,rotor)

FLUENT/UNS (3D)

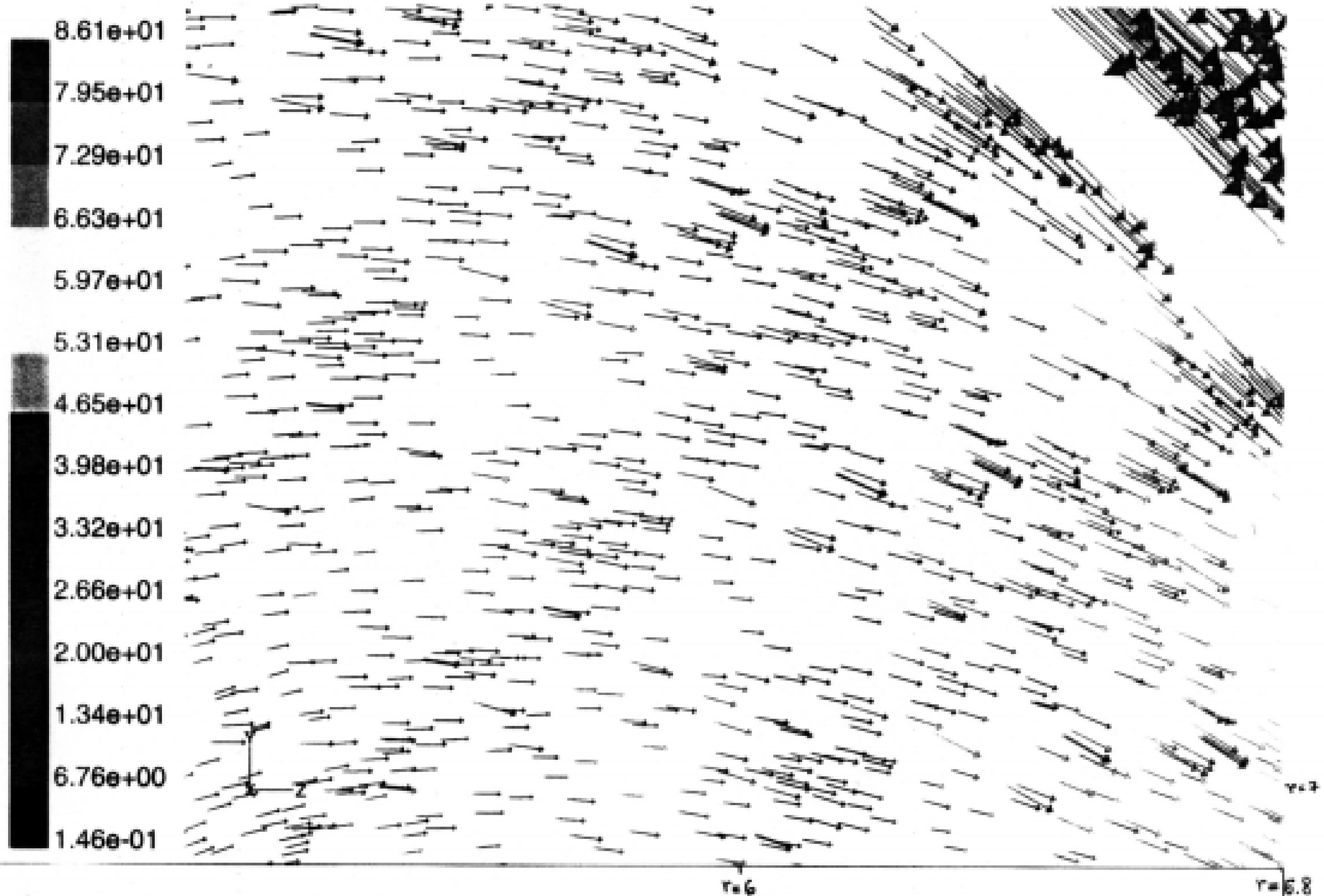
I



2mm from the rotor surface
x = 5" y = 5"
Main flow = 1950 cfm
Cooling flow = 50 cfm
rotor rpm =2000

III

8 m/s



velocity vectors (50cfm,2000rpm,d=2mm,rotor)

III

FLUENT Simulation
(3D)